

8-20-2017

Biochar: From ligno-cellulosic materials to engineered products for environmental services

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Manuel Garcia-Perez, "Biochar: From ligno-cellulosic materials to engineered products for environmental services" in "Biochar: Production, Characterization and Applications", Franco Berruti, Western University, London, Ontario, Canada Raffaella Ocone, Heriot-Watt University, Edinburgh, UK Ondrej Masek, University of Edinburgh, Edinburgh, UK Eds, ECI Symposium Series, (2017). <http://dc.engconfintl.org/biochar/83>

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From Lignocellulosic Materials to Engineered Products for Environmental Services

Manuel Garcia-Perez, Matt Smith, Waled Suliman

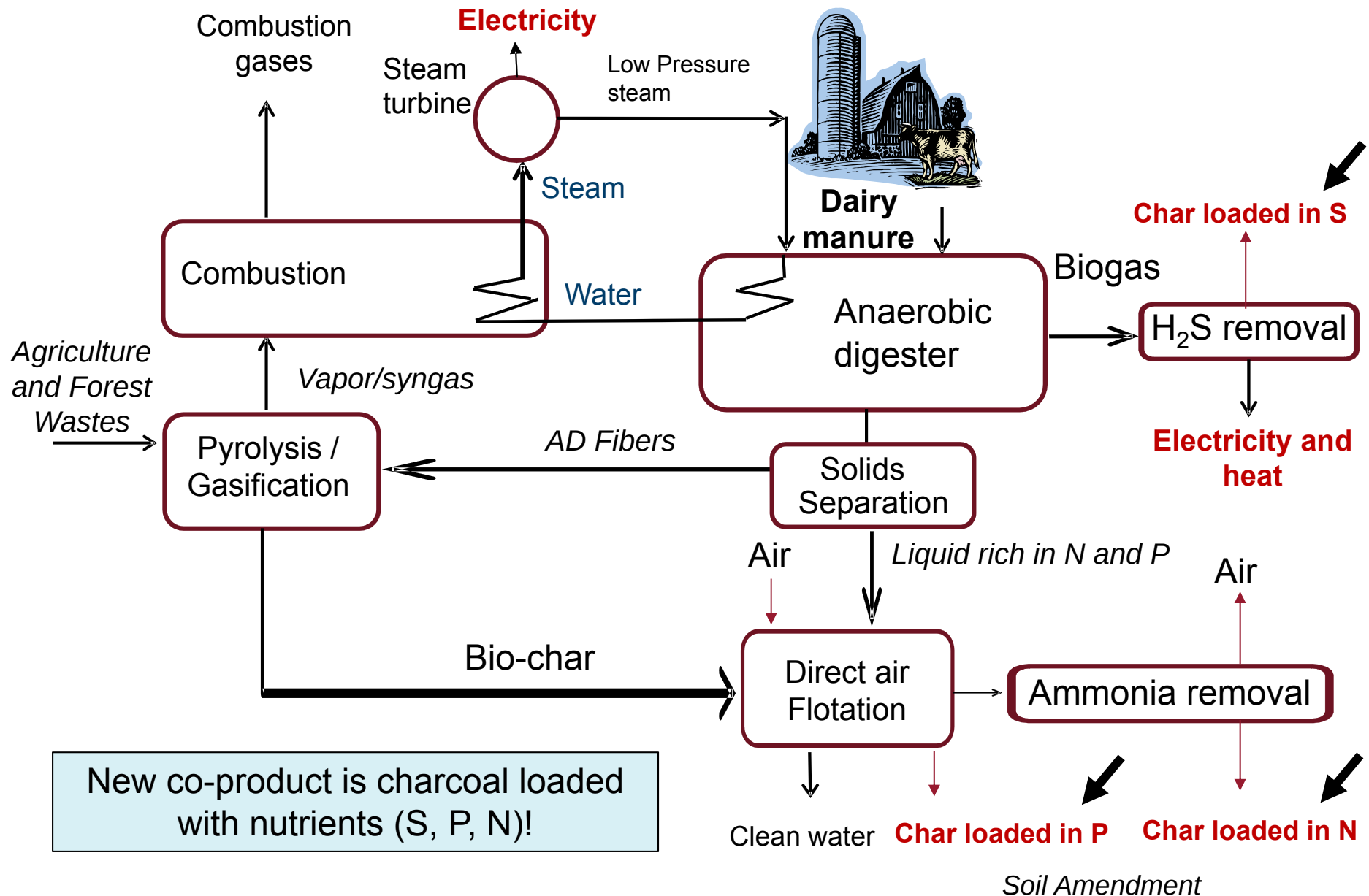
Conference: Bio-char: Production, Characterization and Applications

Engineering Conference International

August 20-25

Hotel Calissano, Alba, Italy

Introduction (WSU AD bio-refinery concept)



Introduction



Development of Cheap Engineered Bio-chars for Nutrient Removal

Ammonium Removal: Air stripping and ammonia collection in gas phase

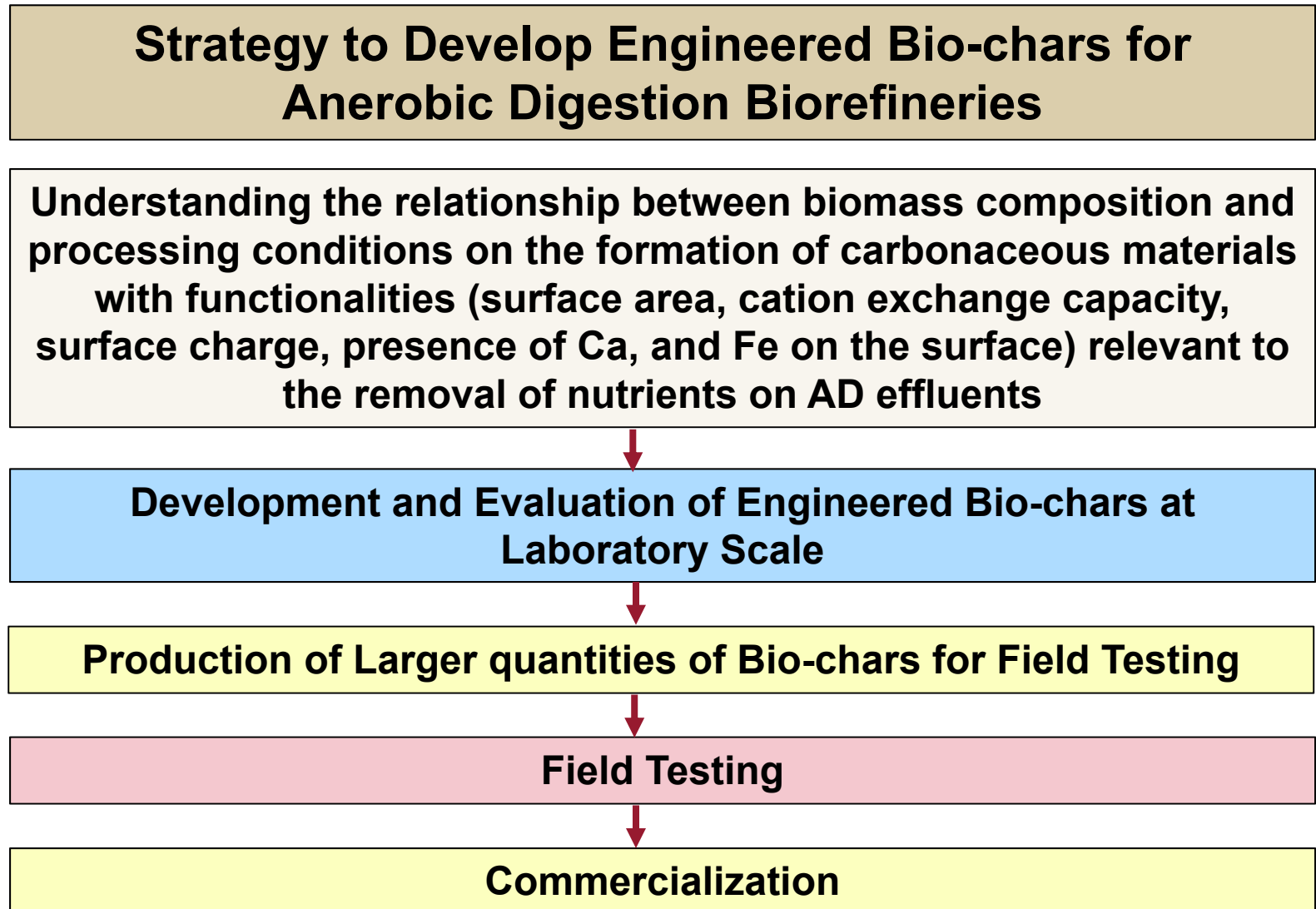
Phosphate Removal: Colloidal Phosphorous Filtration and Phosphate ions precipitation on Ca and Fe

E-coli Retention: Adsorption on Positively Charged Bio-chars

Removal of Organic Pollutants: Adsorption on high surface area materials (Physical Adsorption)

Introduction

Social impact increases, Research and Development Costs augment dramatically, Capacity to train student and Publish in Peer Reviewed Journals decreases



Introduction

Environmental Pollutants

Organic Molecules: Catechol, Phenol, Sulfamethazine

Heavy Metals: Pb (II), Cu (II), Cr (VI), Zn (II)

Inorganics: Phosphate, nitrates

Gases: CO, CO₂, NO, CH₄

Mechanisms for the Removal of Environmental Pollutants

Pore Filling

Diffusion and partitioning

Formation of surface complexes

Aromatic π - π interactions

Hydrogen bonding

Electrostatic interactions

Interaction with amine groups

Precipitation

Hydrophobic interactions

Cation Exchange

Simultaneous adsorption/catalytic degradation

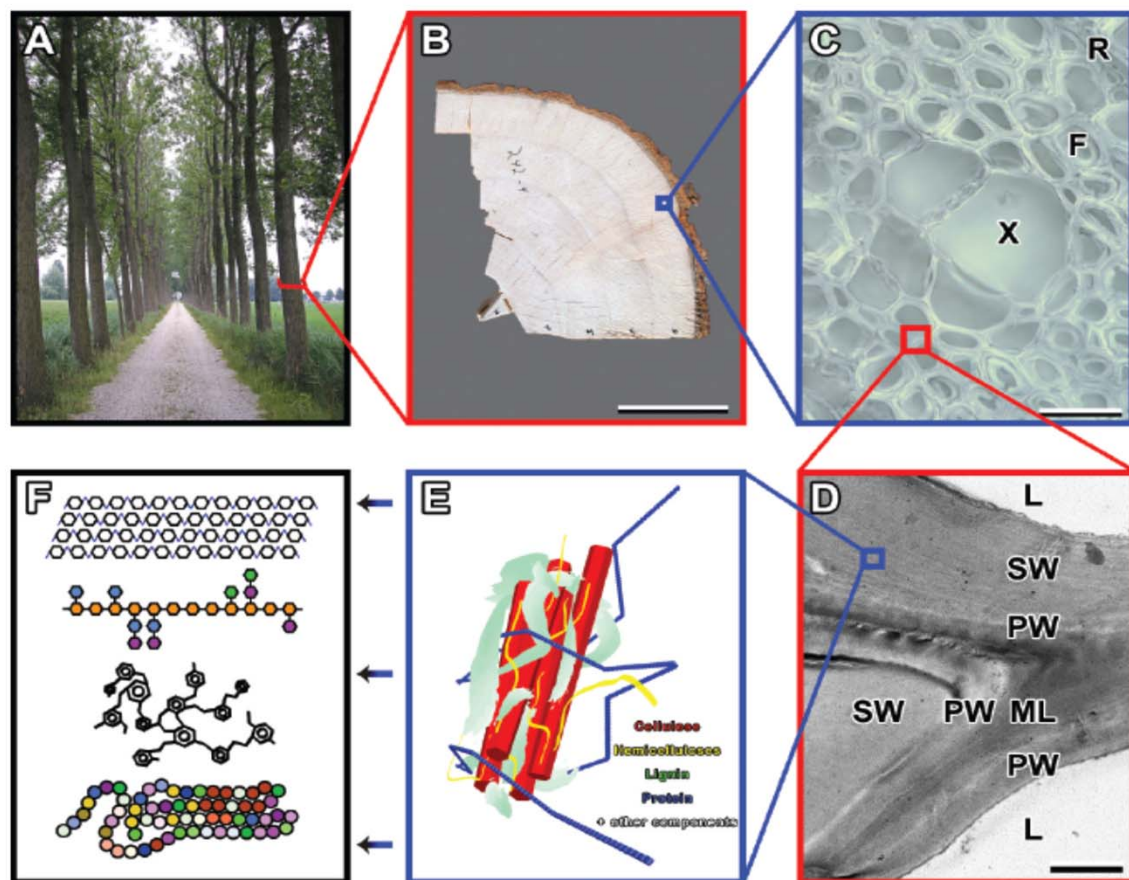
Induced Precipitation

Micro-organism mediated

**What are the bio-char structure associated to each of these mechanisms?
How can we enhance the formation of carbonaceous structures relevant for
targeted pollutant removal?**

Introduction

Scale down through biomass from the organismal to the molecular level



(A) populus sp (B) poplar wood (C) cross section of a poplar sample. Cell types: X- xylem element, F: wood fiber R: ray parenchyma (D) transmission electron microphotograph of a poplar xylem (E) artistic representation of the plant cell wall macromolecular structure, red, cellulose microfibrils, yellow hemicellulose and pectins green: lignin, blue structural proteins. (F) artistic representation of plant cell wall polymers (from top) cellulose hemicelluloses, lignin and protein

Source: Haas T.J., Nimlos M.R., Donohoe B.S.: Real-time and post-reaction microscopic structural analysis of biomass undergoing pyrolysis. Energy & fuels 2009, 23, 3810-3817.

Introduction

The **cell wall** is built up by several layers:

(1) Middle Lamella **ML**

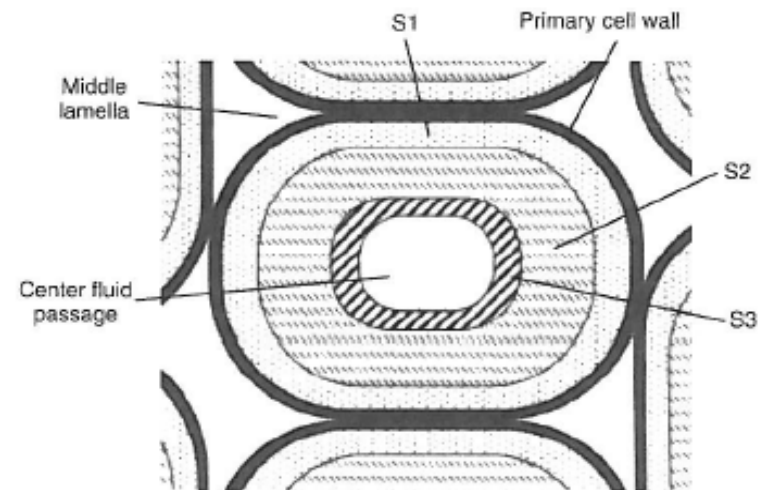
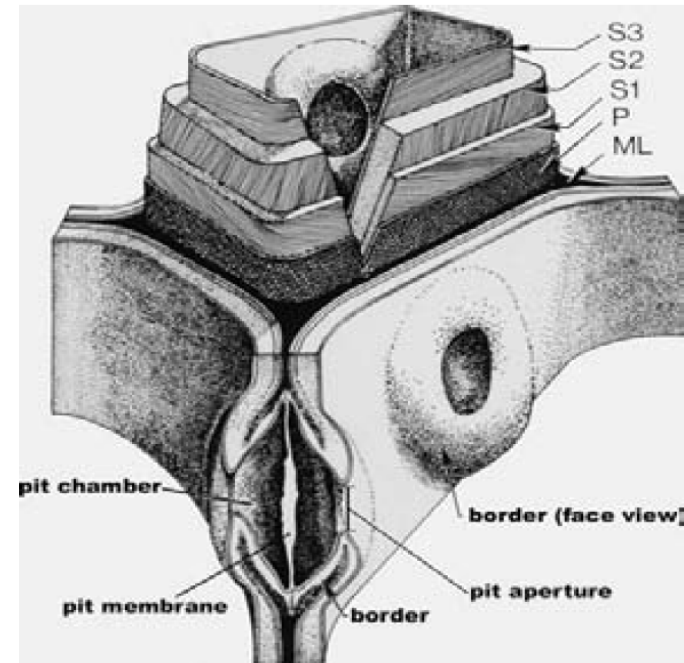
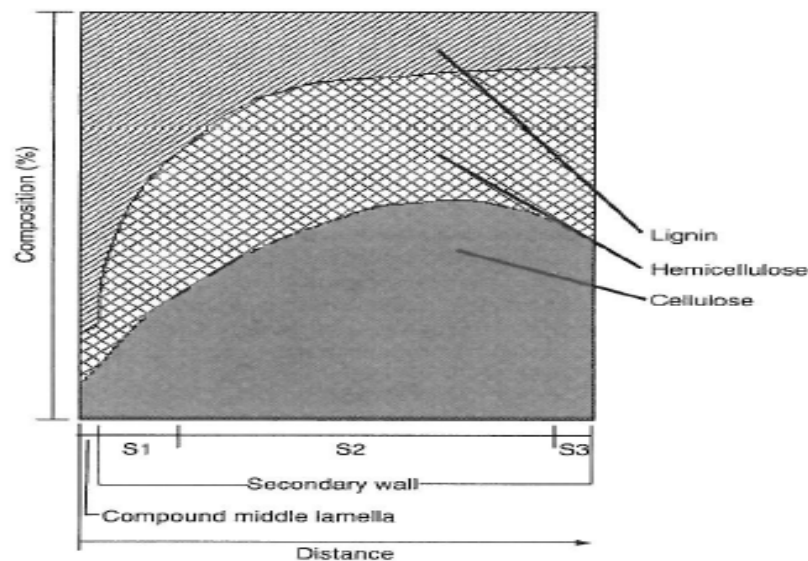
(2) Primary Wall (**P**)

Binds the cells together

(3) Outer Layer of the Secondary Wall (**S₁**)

(4) Middle Layer of the Secondary Wall (**S₂**)

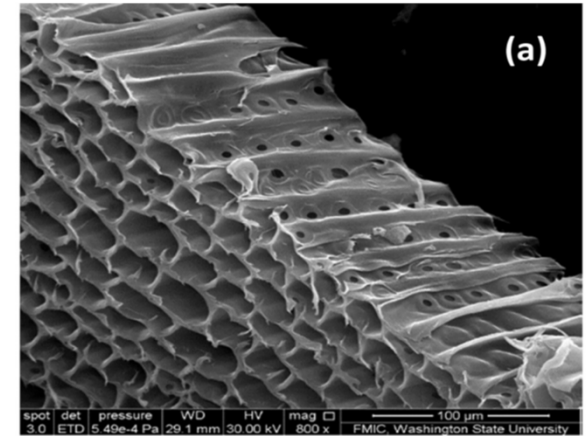
(5) Inner Layer of the Secondary Wall (**S₃**)



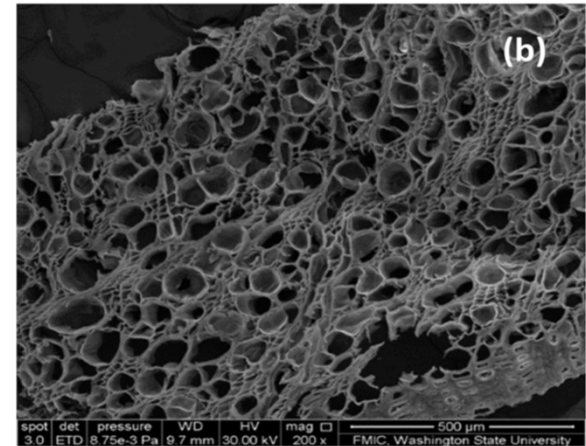
Introduction

**Biochar
conserves the
structure of the
Lignocellulosic
Material!**

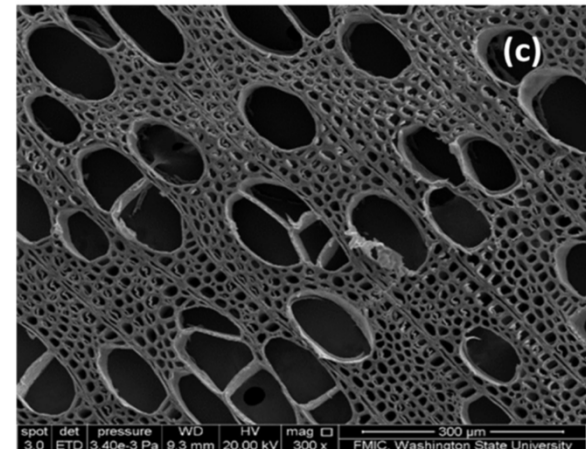
Douglas Fir Wood Char



Douglas Fir Bark Char

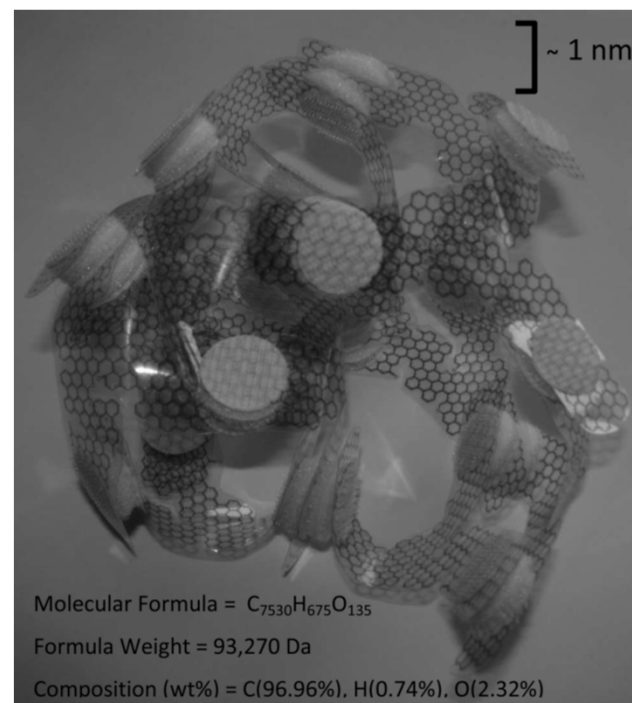
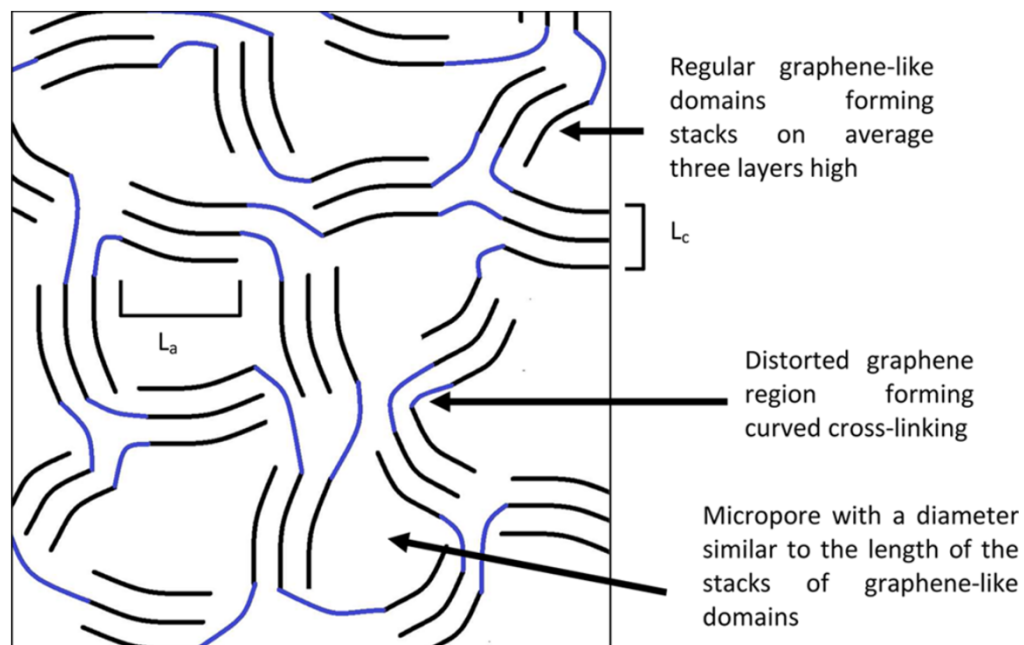


Hybrid Poplar



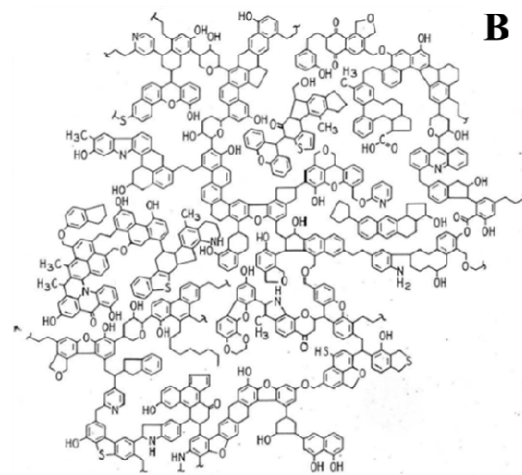
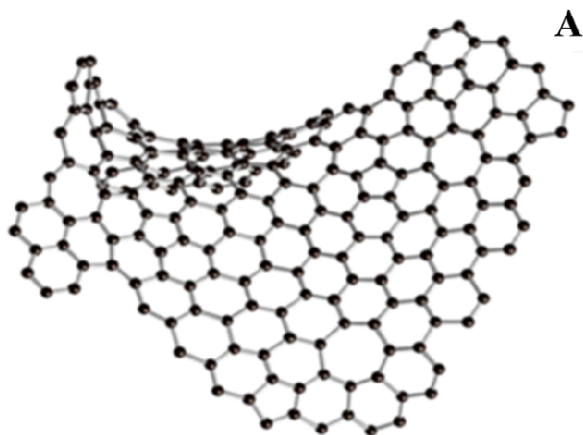
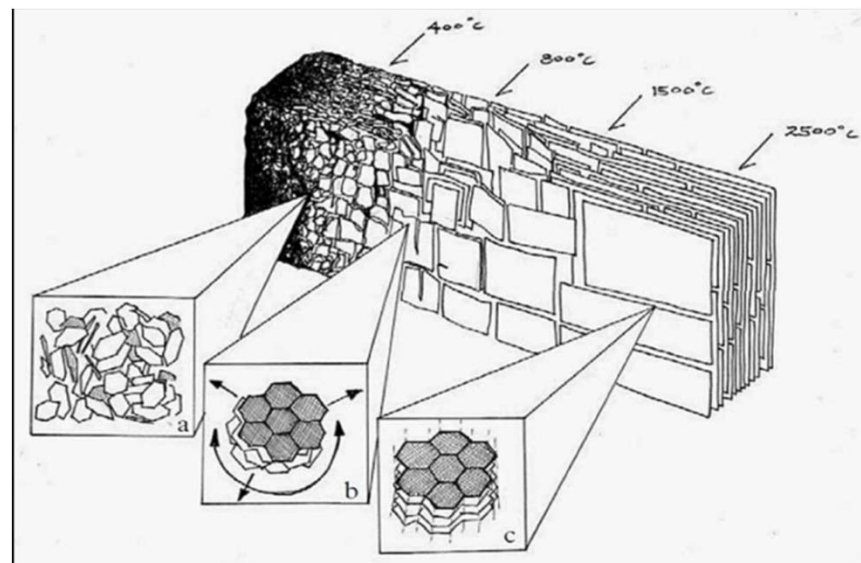
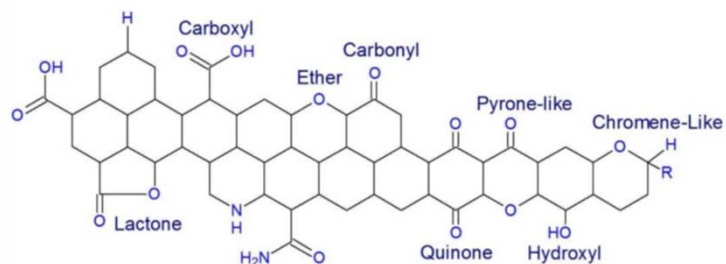
Introduction

McDonald-Wharry et al. 2016



McDonald-Wharry J S, Manley-Harris M, Pickering K L. Reviewing, Combining, and Updating the Models for the Nanostructure of Non-Graphitizing Carbons Produced from Oxygen-Containing Precursors. Energy and Fuels 2016.

Introduction



Shinn JH. From coal to single-stage and two-stage products: A reactive model of coal structure. *Fuel*. 1984;63(9):1187-96.

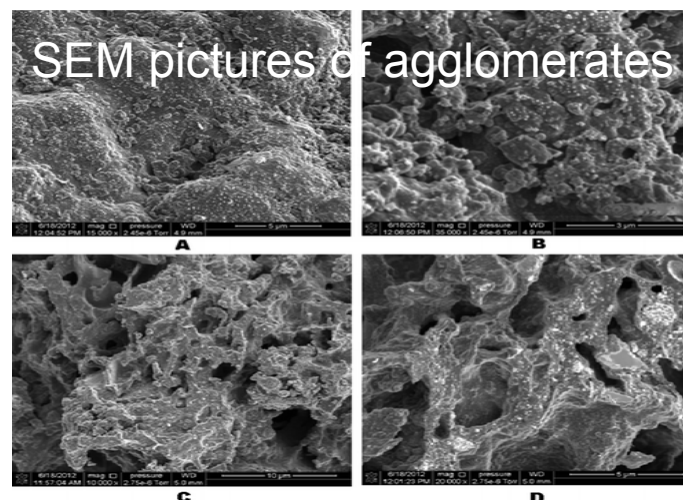
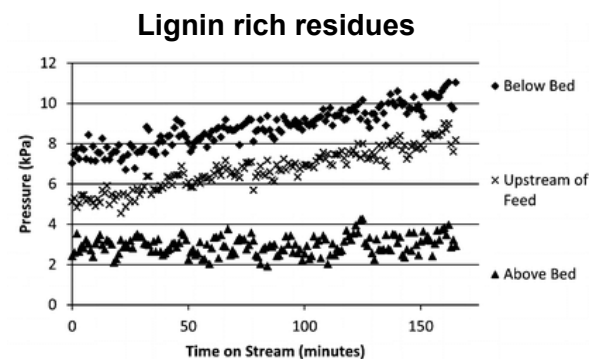
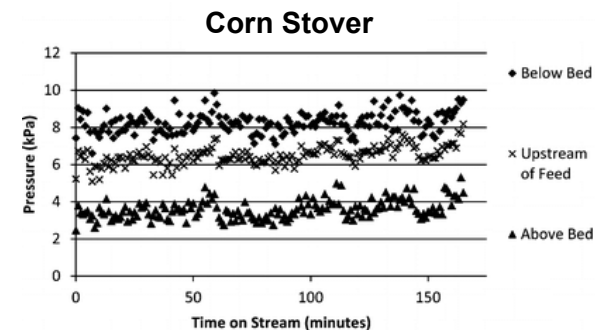
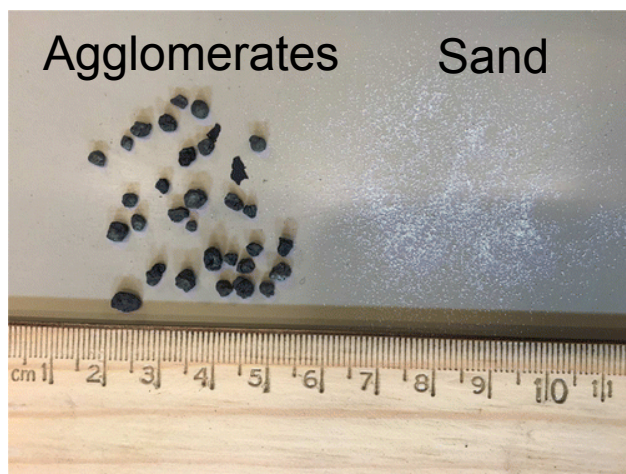
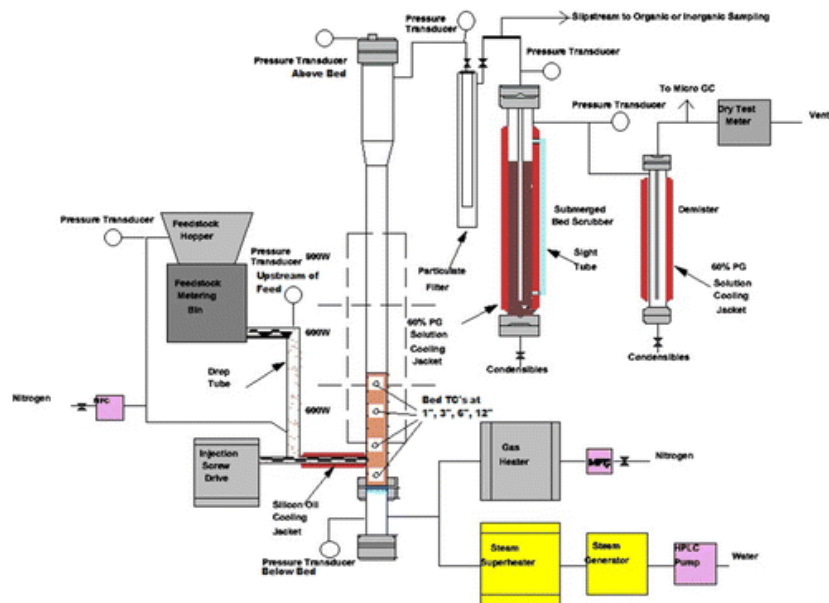
Harris PJF, Liu Z, Suenaga K. Imaging the atomic structure of activated carbon. *Journal of Physics: Condensed Matter*. 2008;20(36):362201.

Turpin E, *Architecture in the Anthropocene: Encounters Among Design, Deep Time, Science and Philosophy* Turpin, E. (ed) Open Humanities Press

Chia C, Downie A, Munroe P: *Biochar for environmental Management* second. Lehmann J and Joseph (eds.), Earthscan, Routledge, UK, New York, NY, 2015

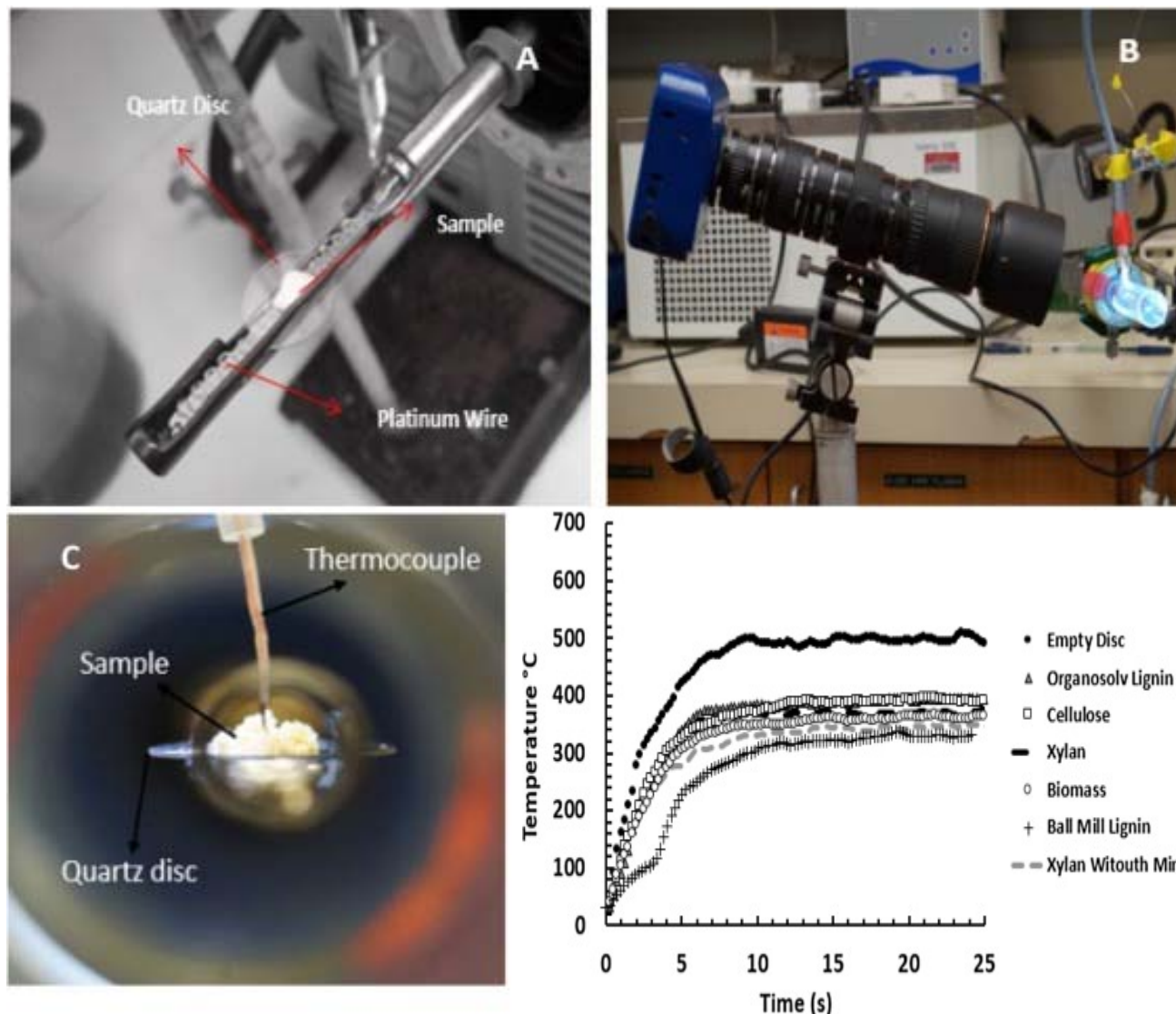
Formation of liquid intermediates (fundamentals)

Gasification System



Howe D, Taasevigen D, Gerber M, Gray M, Fernandez C, Saraf L, Garcia-Perez M, Wolcott M: Bed Agglomeration during steam gasification of a high lignin corn stover simultaneous Saccharification and Fermentation (SSF) Digester Residue. Energy Fuels, 2015, 29 (12), 8035-8046

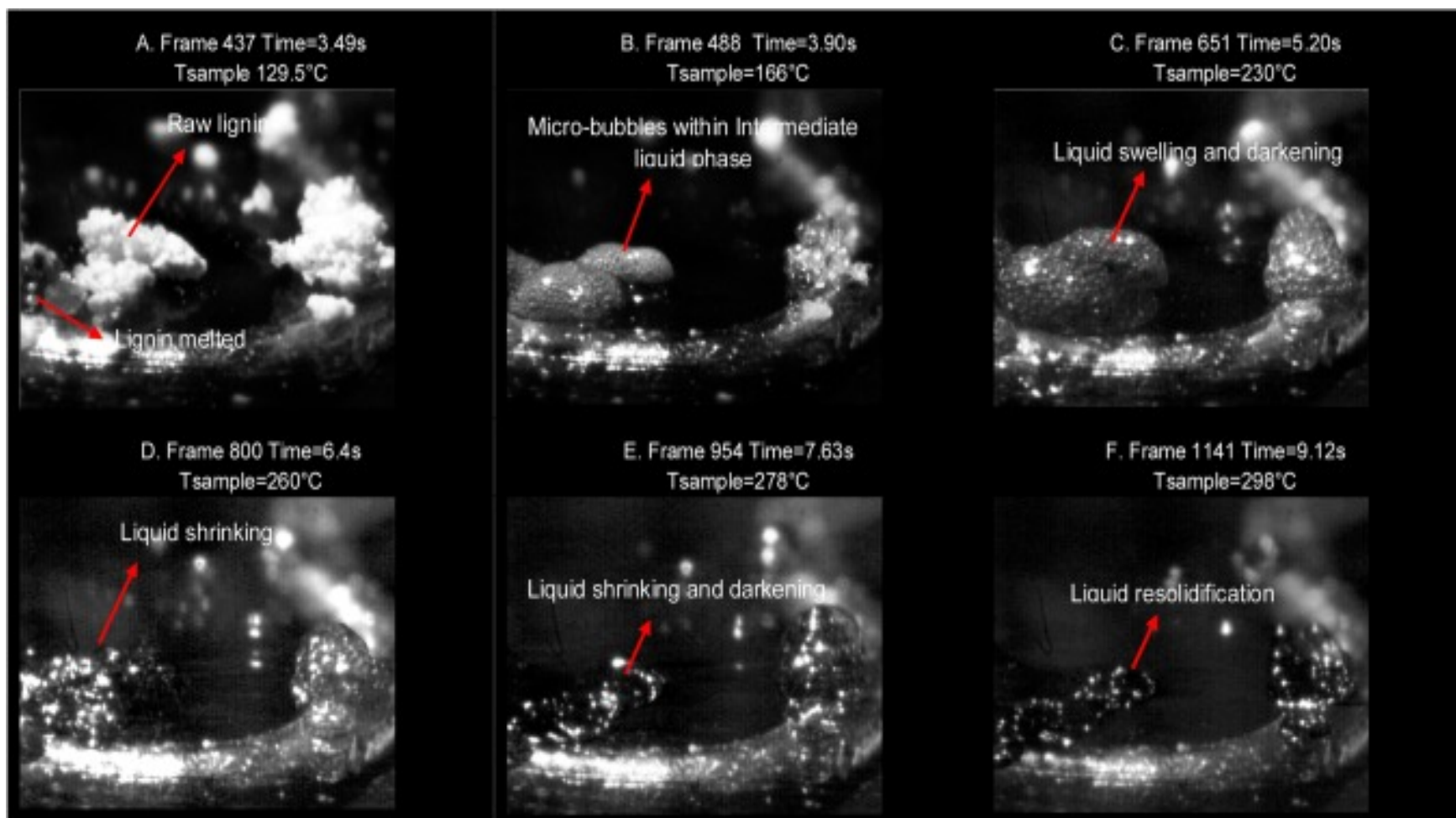
Formation of liquid intermediates (Fundamentals)



Montoya J, Pecha B, Chejne-Janna F, Garcia-Perez M: Micro-Explosion of Liquid intermediates During the Fast Pyrolysis of Sucrose and organosolv Lignin. Journal of Analytical and Applied Pyrolysis 2016, 122, 106-121

Formation of liquid intermediates

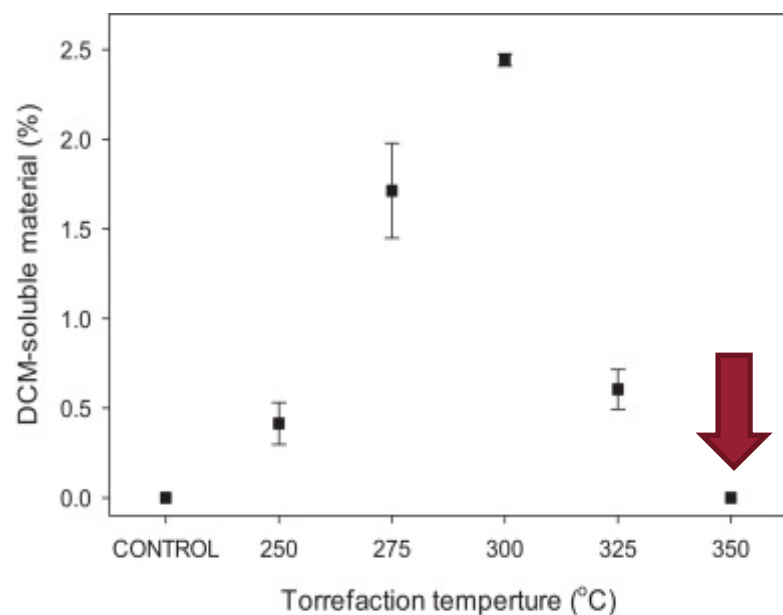
Formation of liquid Intermediates from Milled wood lignin



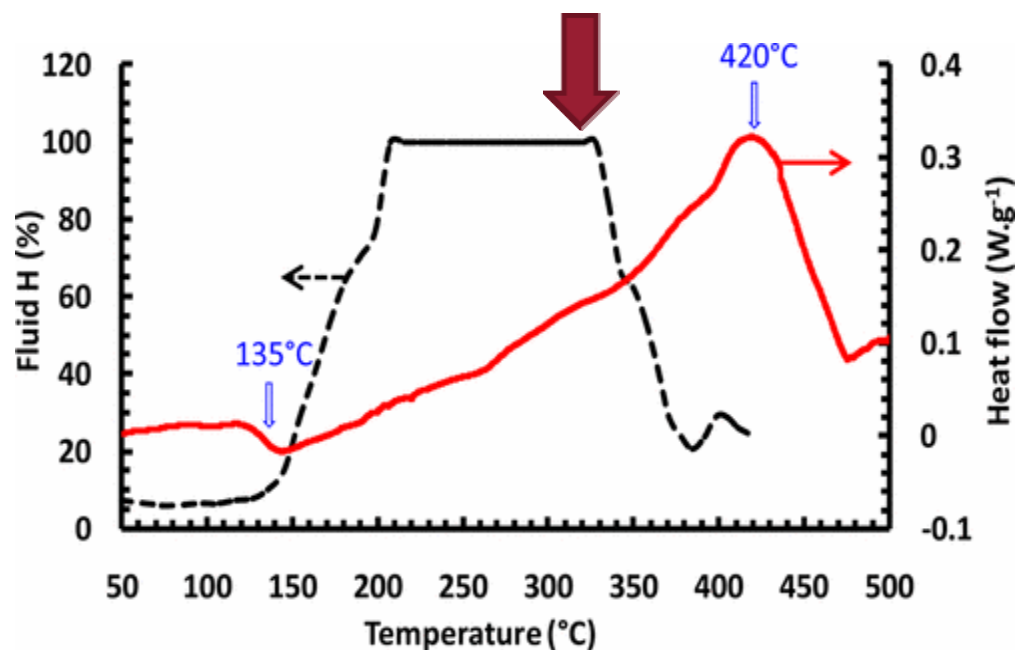
Montoya J, Pecha B, Chejne-Janna F, Garcia-Perez M: Identification of the fractions responsible for morphology conservation in lignocellulosic pyrolysis: Visualization studies of sugarcane bagasse and its pseudo-components. Journal of analytical and applied pyrolysis. 2017, 123, 307-318

Formation of liquid intermediates

Low molecular weight Oligomers
(extractable with DCM)
(Torrefaction of Ponderosa pine)



Fluidity development from in situ
 ^1H NMR and DSC (From Dr.
Doufor's group)

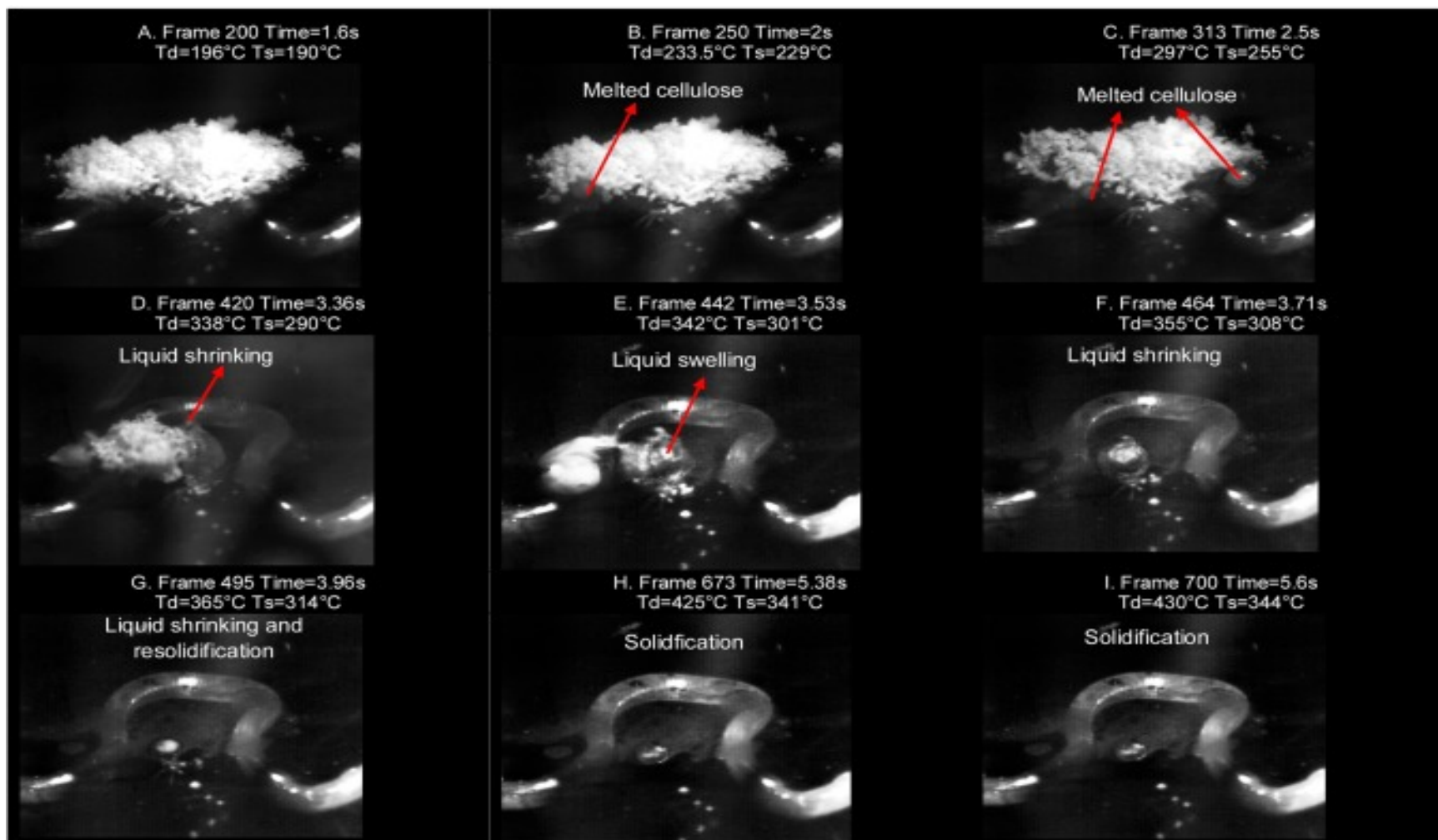


Pelaez-Samaniego MR, Vikram Y, Garcia-Perez M, Lowell E, McDonald AG: Effect of temperature during wood torrefaction on the formation of lignin liquid intermediates. *Journal of Analytical and Applied Pyrolysis*. 109, 2014, 222-233

Shrestha B, Le Brench YL, Ghislain T, Leclerc S, Carre V, Aubriet F, Hoppe S, Marchal P, Pontvianne S, Brosse N, Doufor A: A multi-technique characterization of lignin softening and pyrolysis. *ACS Sustainable Chemical Engineering*, 2017, 5 (8), 6940-6949

Formation of liquid intermediates

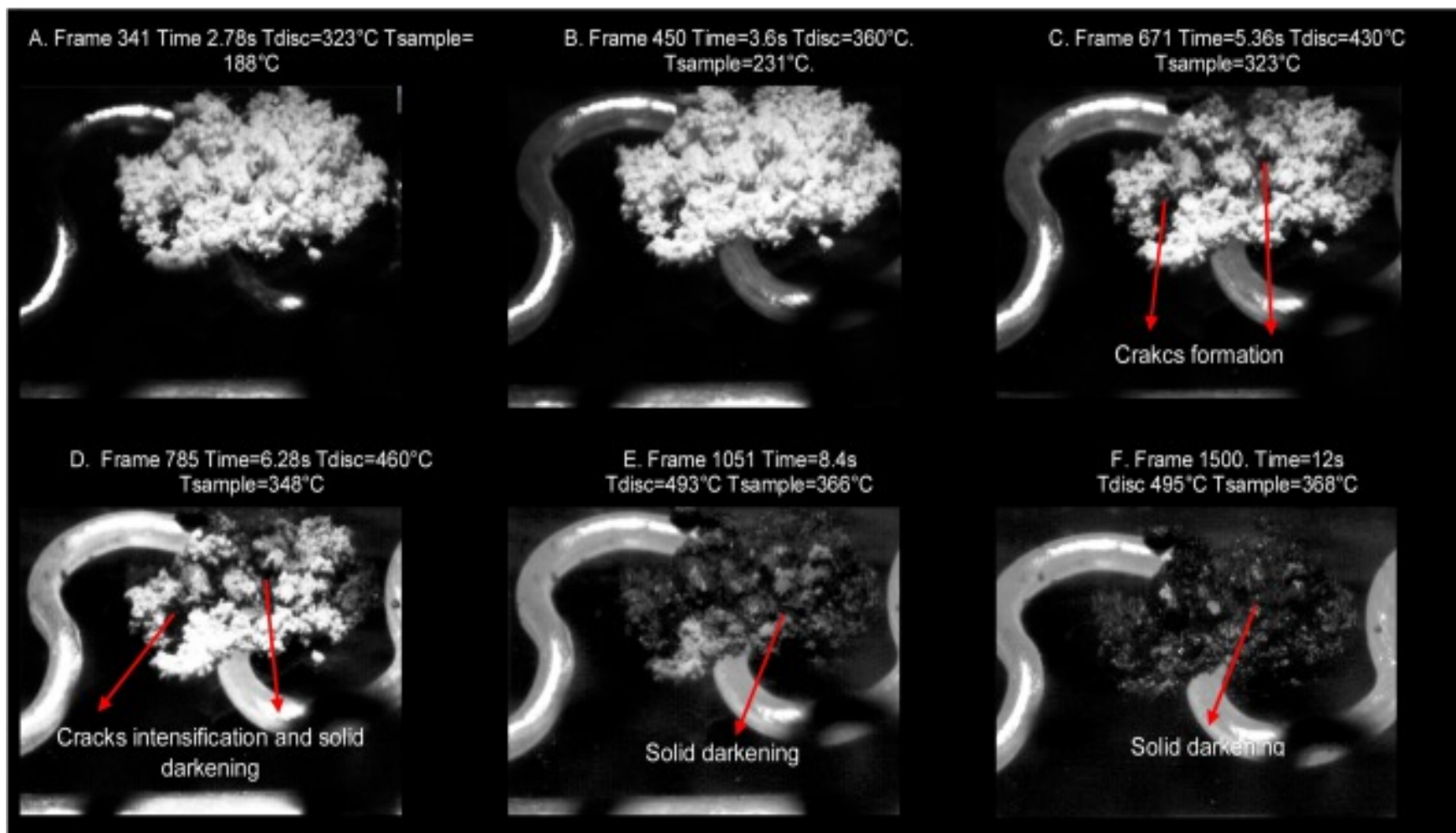
Cellulose melting and bubbling during Pyrolysis



Montoya J, Pecha B, Chejne-Janna F, Garcia-Perez M: Identification of the fractions responsible for morphology conservation in lignocellulosic pyrolysis: Visualization studies of sugarcane bagasse and its pseudo-components. Journal of analytical and applied pyrolysis. 2017, 123, 307-318

Formation of liquid intermediates

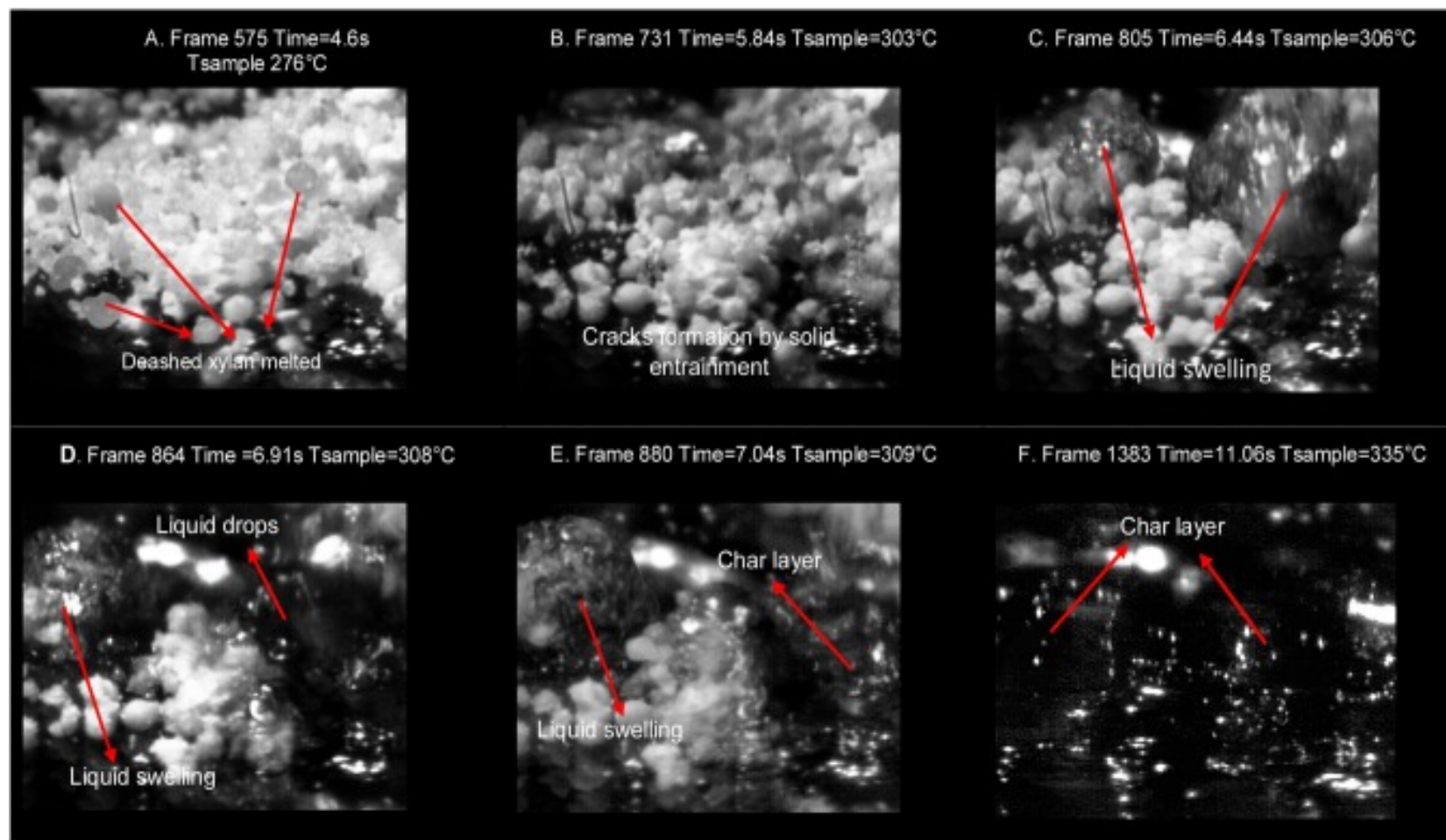
Xylan behavior during Pyrolysis



Montoya J, Pecha B, Chejne-Janna F, Garcia-Perez M: Identification of the fractions responsible for morphology conservation in lignocellulosic pyrolysis: Visualization studies of sugarcane bagasse and its pseudo-components. Journal of analytical and applied pyrolysis. 2017, 123, 307-318

Formation of liquid intermediates

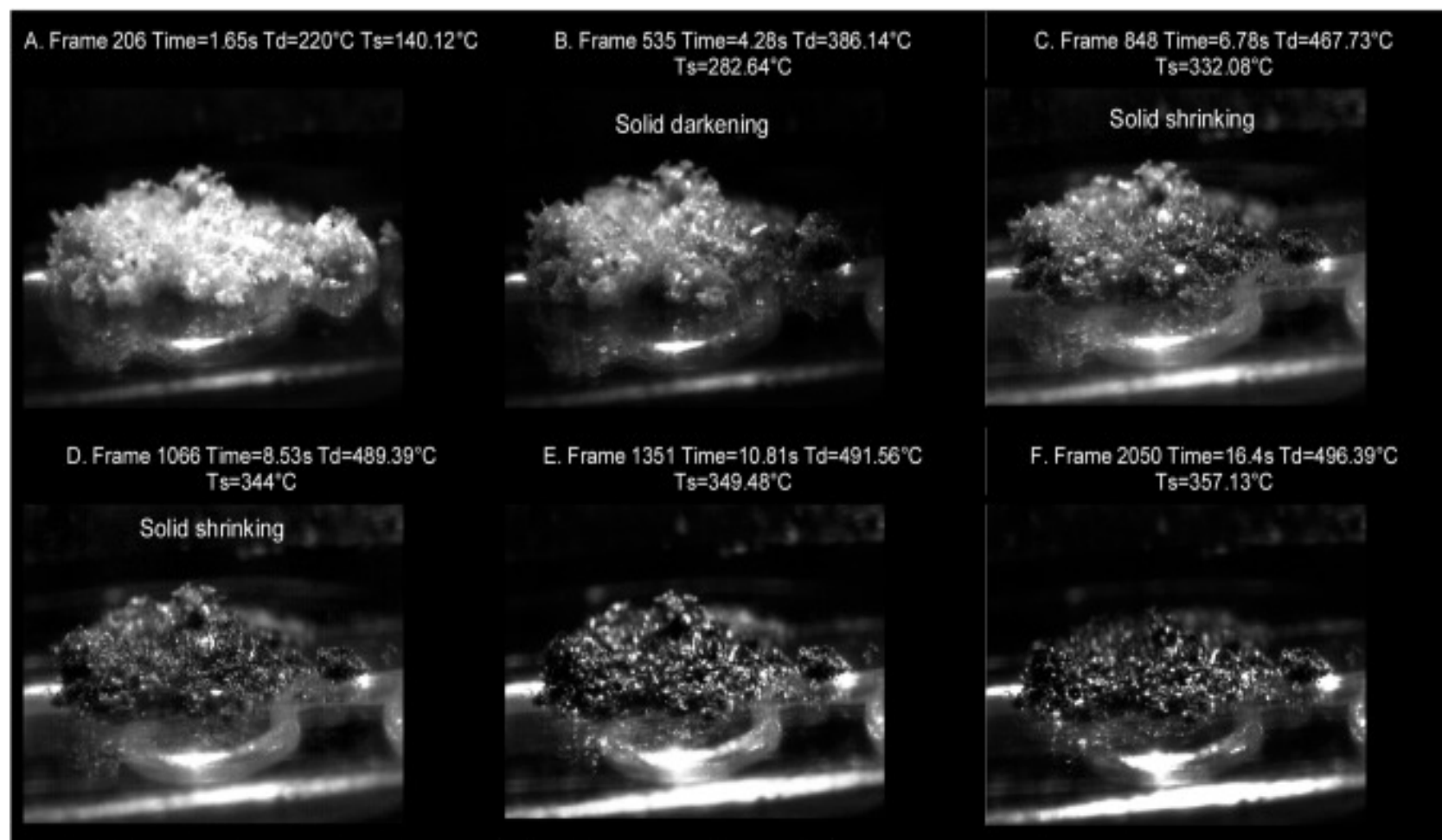
Deashed Xylan behavior during Pyrolysis



Montoya J, Pecha B, Chejne-Janna F, Garcia-Perez M: Identification of the fractions responsible for morphology conservation in lignocellulosic pyrolysis: Visualization studies of sugarcane bagasse and its pseudo-components. Journal of analytical and applied pyrolysis. 2017, 123, 307-318

Formation of liquid intermediates

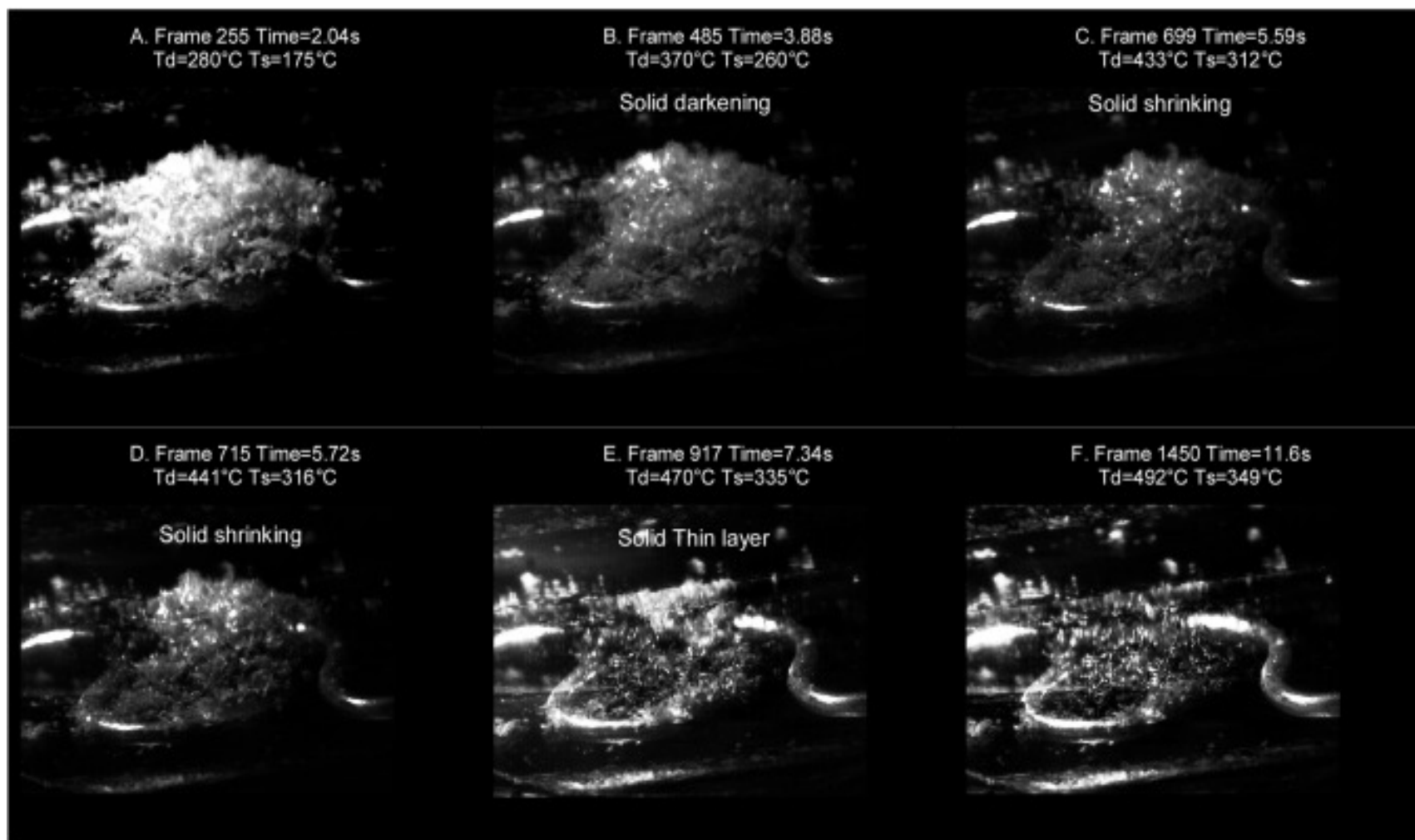
Sugarcane bagasse during Pyrolysis



Montoya J, Pecha B, Chejne-Janna F, Garcia-Perez M: Identification of the fractions responsible for morphology conservation in lignocellulosic pyrolysis: Visualization studies of sugarcane bagasse and its pseudo-components. Journal of analytical and applied pyrolysis. 2017, 123, 307-318

Formation of liquid intermediates

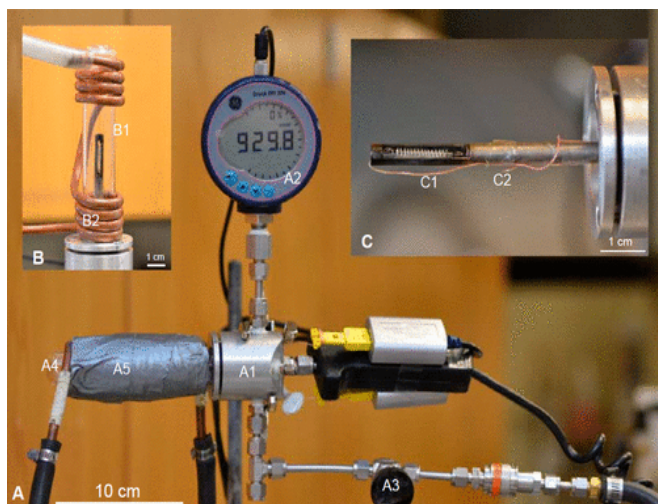
Acid washed sugar cane bagasse



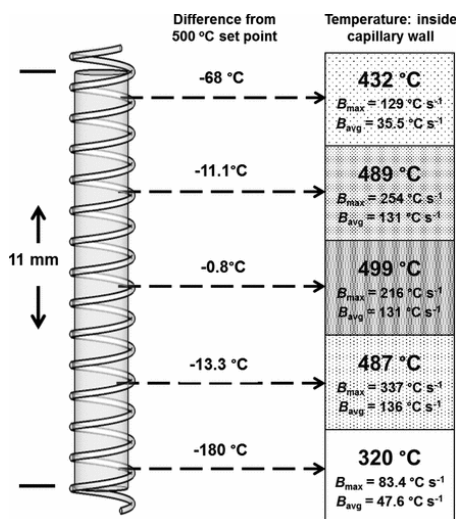
Montoya J, Pecha B, Chejne-Janna F, Garcia-Perez M: Identification of the fractions responsible for morphology conservation in lignocellulosic pyrolysis: Visualization studies of sugarcane bagasse and its pseudo-components. Journal of analytical and applied pyrolysis. 2017, 123, 307-318

Formation of liquid intermediates

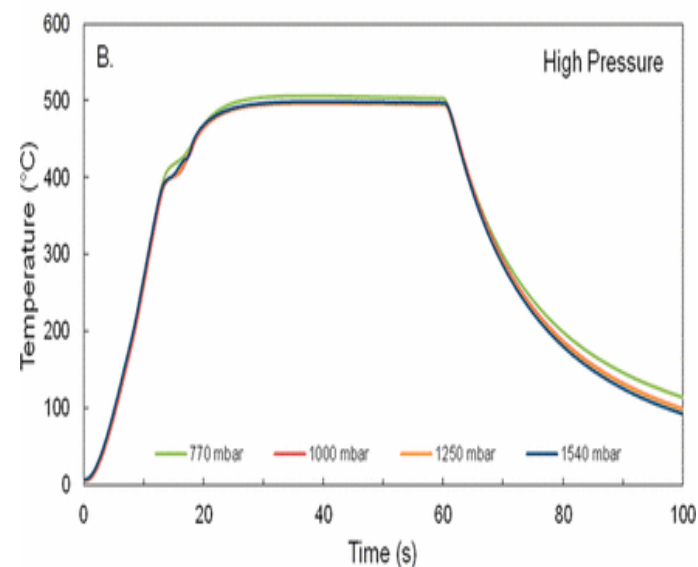
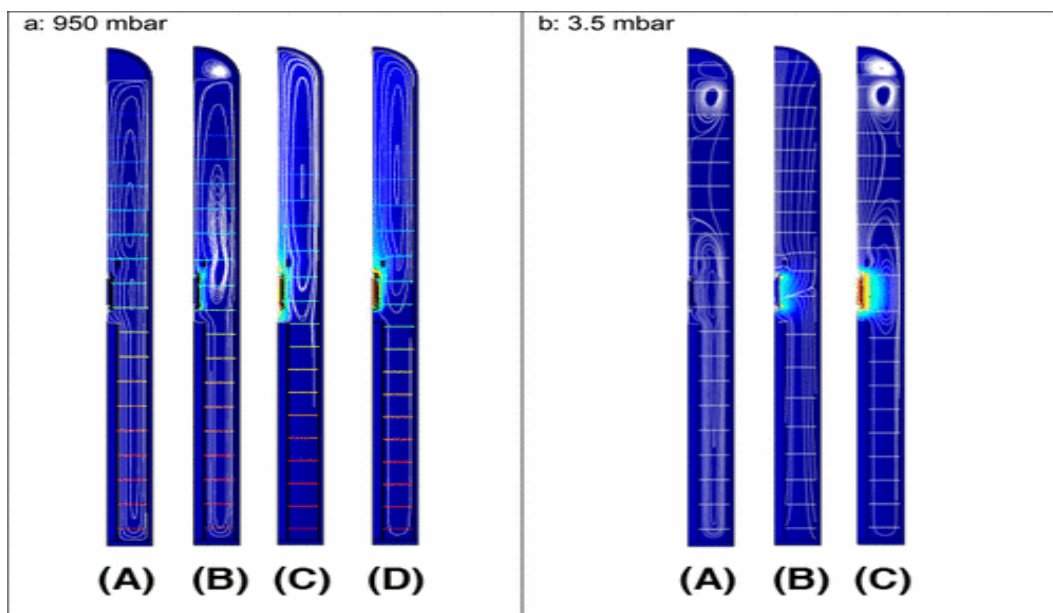
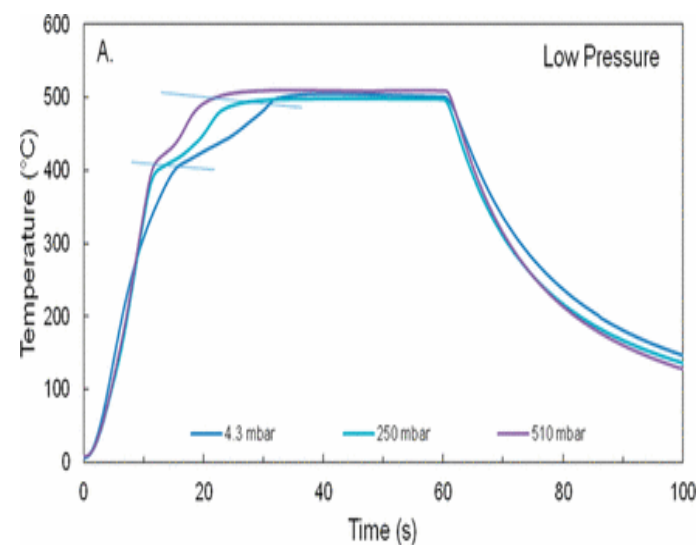
Modified Pyro-probe



Temperature profile



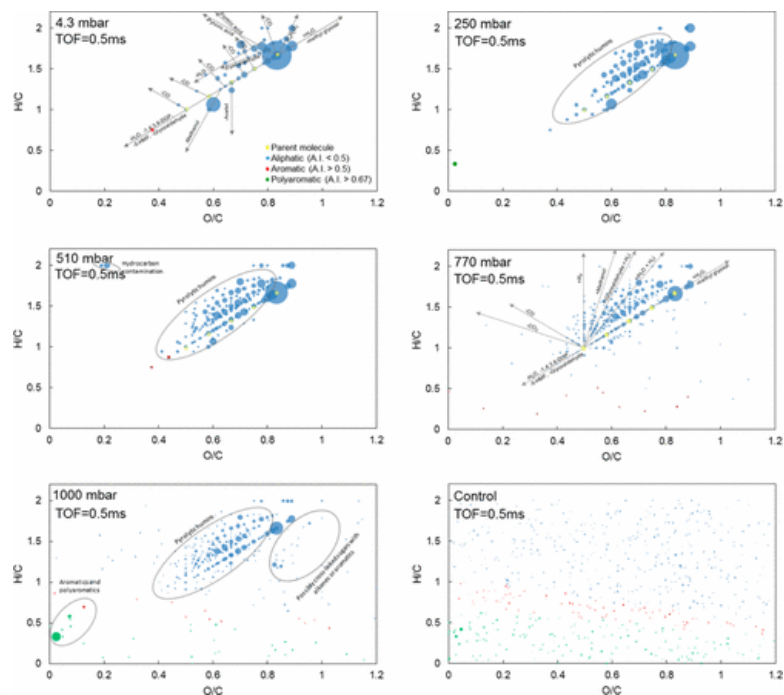
Temperature profile



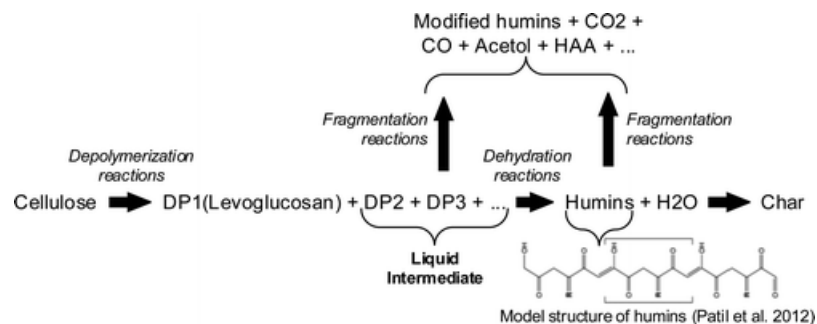
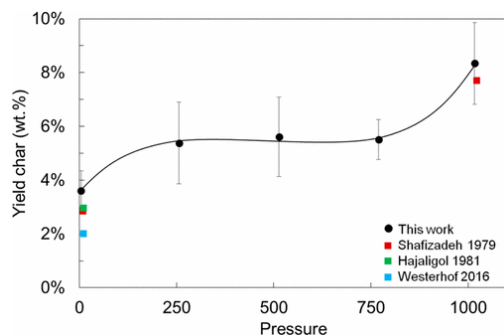
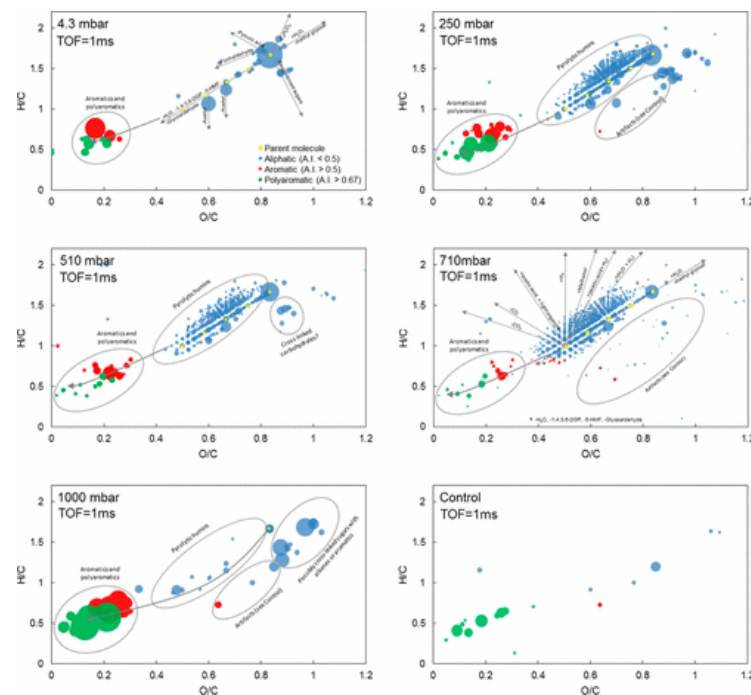
Formation of liquid intermediates

Reactions in the Liquid Intermediates (Cellulose) (FT-ICR-MS)

Small Oligomers



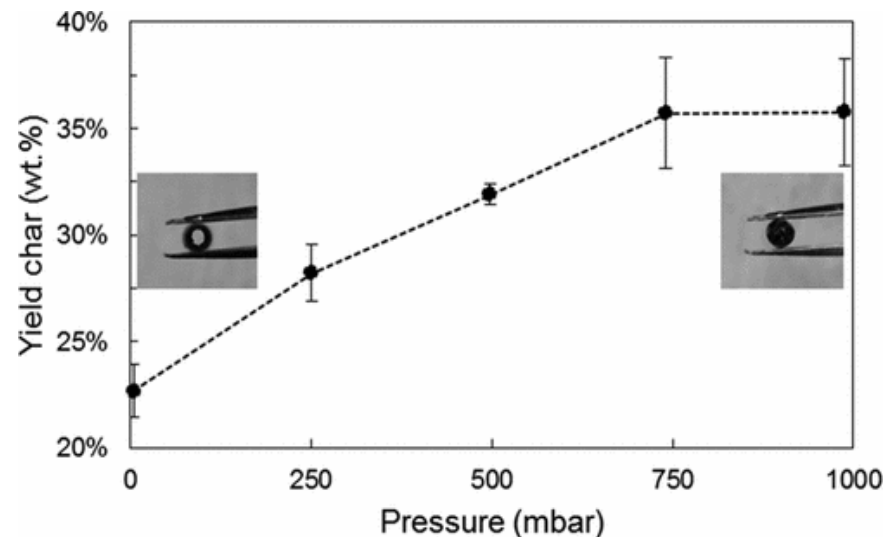
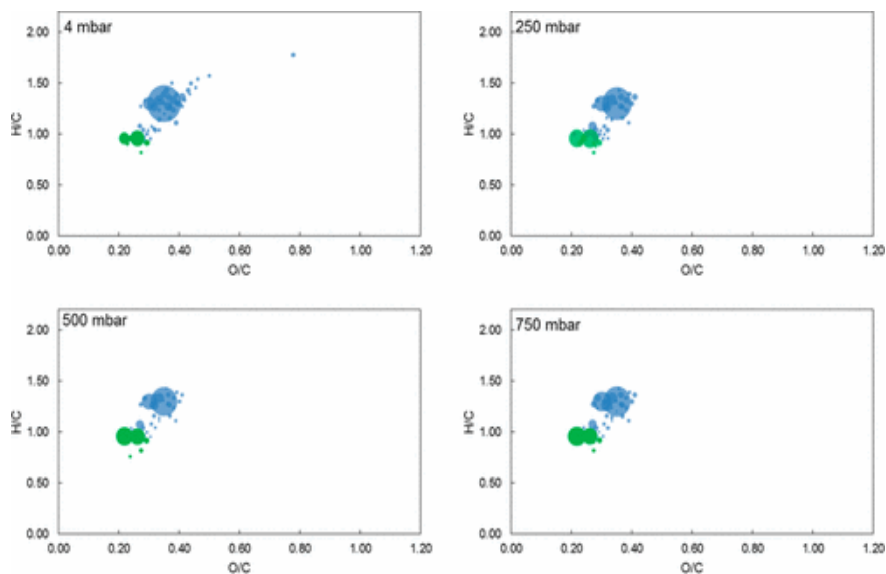
Large Oligomers



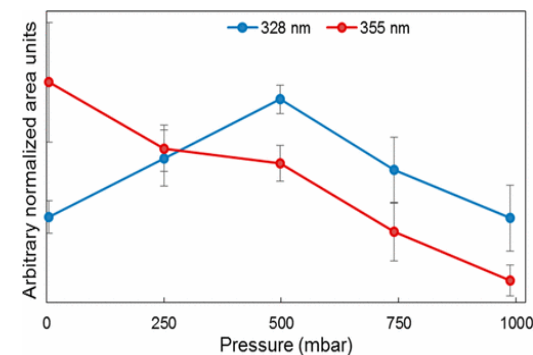
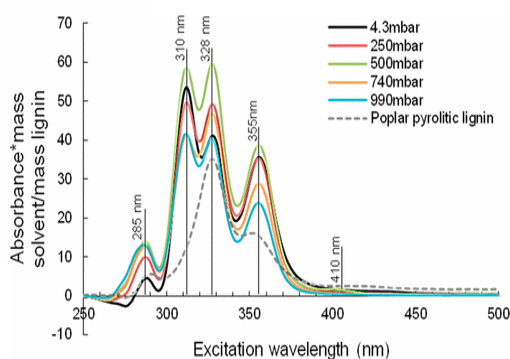
Pecha BM, Montoya JI, Chejne F, Garcia-Perez M: Effect of a Vacuum on the fast Pyrolysis of cellulose: Nature of Secondary Reactions in a Liquid Intermediate. *Ind. Eng. Chem. Res.*, 2017, 56 (15), 4288-4301

Formation of liquid intermediates

Reactions in the Liquid Intermediates (Lignin) (FT-ICR-MS)



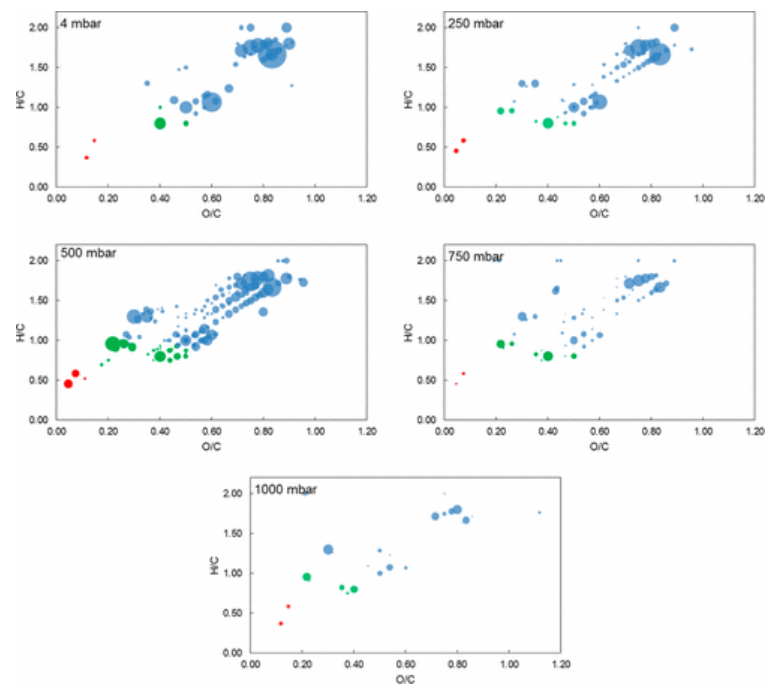
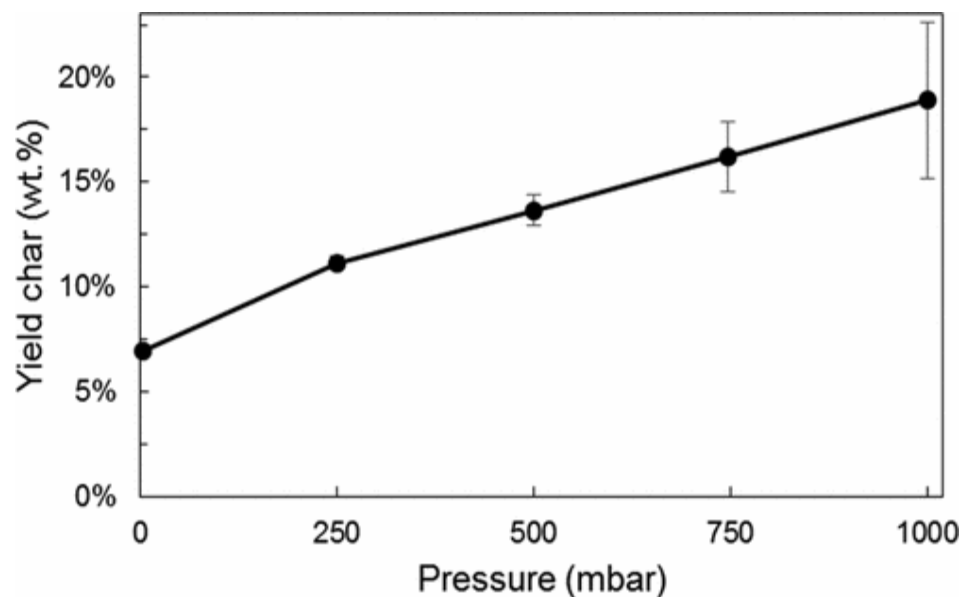
UV-Fluorescence



Pecha BM, Terrell E, Montoya JI, Stankovikj F, Broadbelt LJ, Chejne F, Garcia-Perez M: Effect of Pressure on Pyrolysis of Milled Wood Lignin and Acid-Washed Hybrid Poplar Wood. *Ind. Eng. Chem. Res.*, 2017, In press

Formation of liquid intermediates

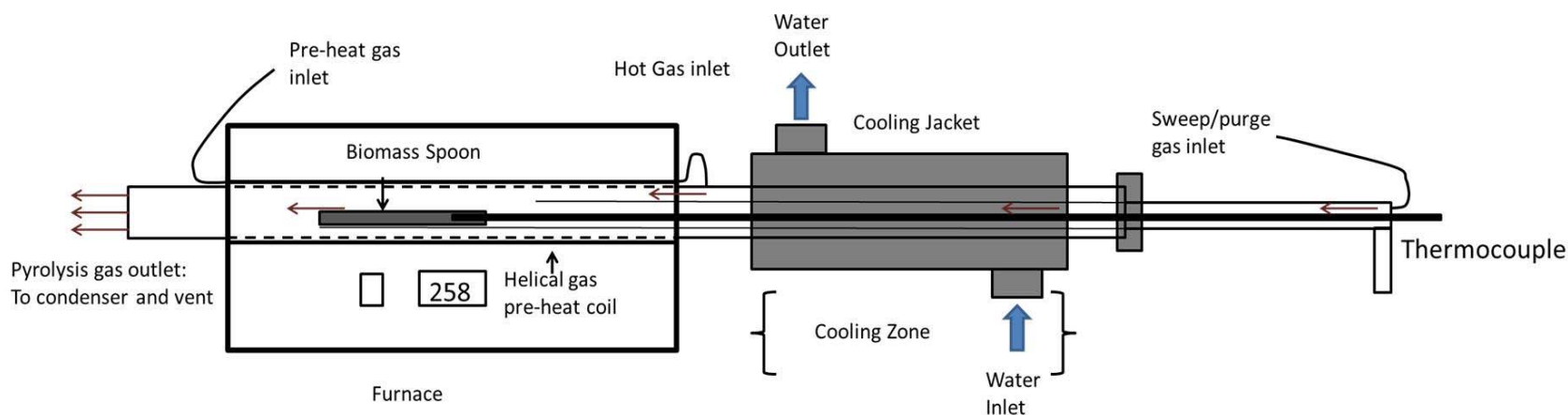
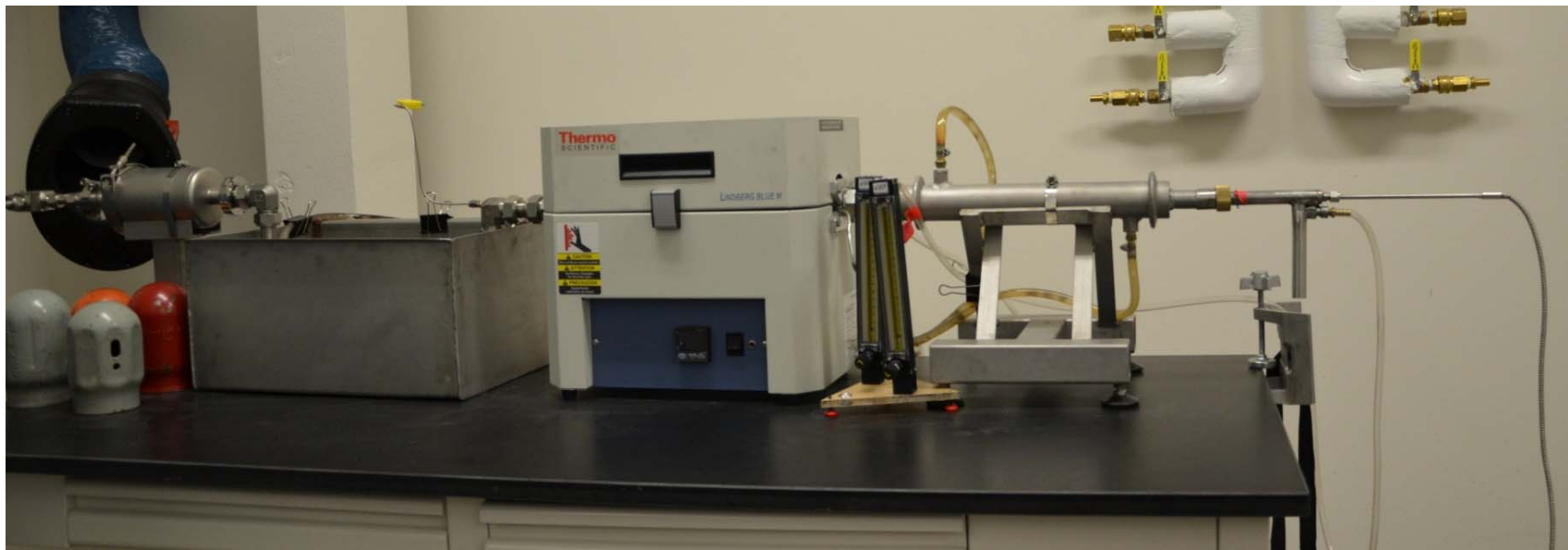
Reactions in the Liquid Intermediates (Sugarcane Bagasse) (FT-ICR-MS)



Pecha BM, Terrell E, Montoya JI, Stankovikj F, Broadbelt LJ, Chejne F, Garcia-Perez M: Effect of Pressure on Pyrolysis of Milled Wood Lignin and Acid-Washed Hybrid Poplar Wood. *Ind. Eng. Chem. Res.*, 2017, In press

Biochar Formation Mechanisms

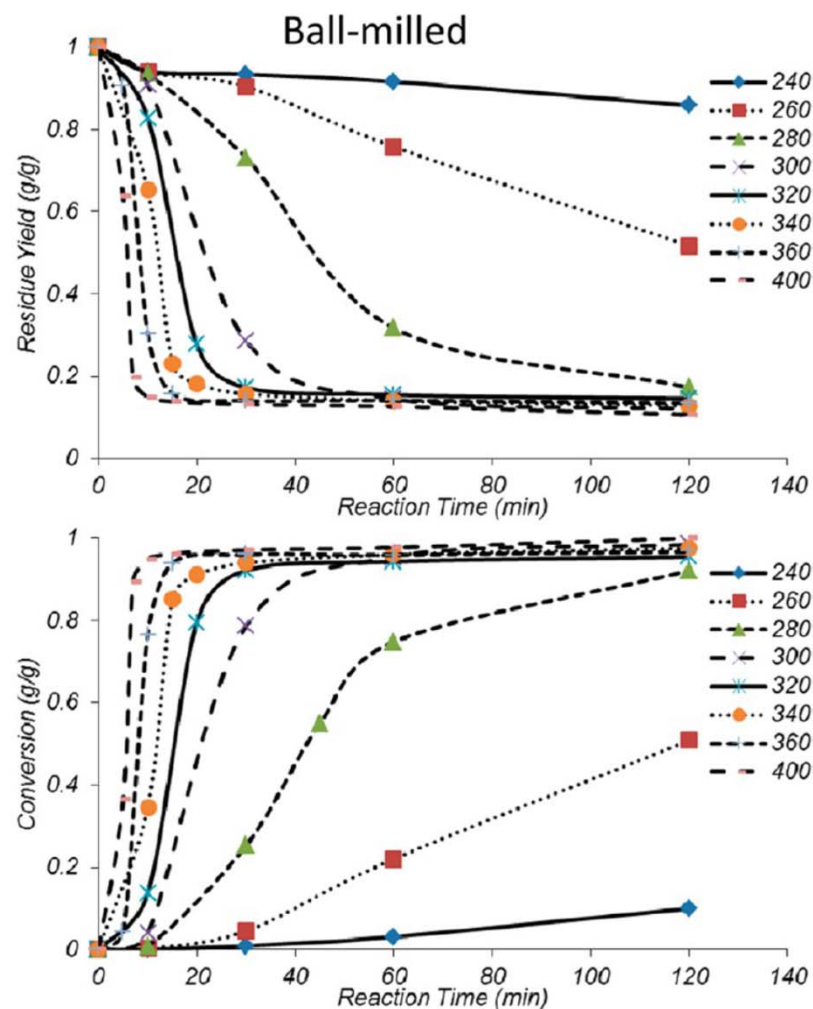
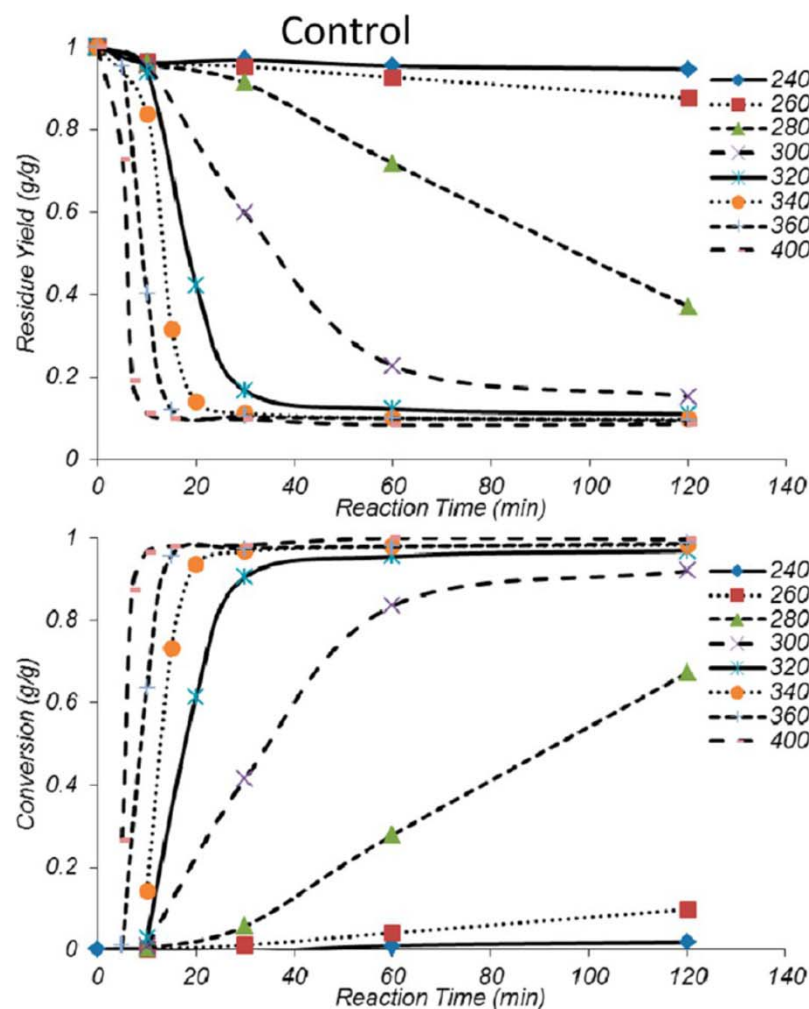
Spoon Reactor



Wang Z, Pecha B, Westerhof RJM, Kersten SRA, Li C-Z, McDonald AG, Garcia-Perez M: Effect of Cellulose Crystallinity on Solid/Liquid Phase Reactions Responsible for the Formation of Carbonaceous Residues during Pyrolysis. Industrial & Engineering Chemistry Research, 2014, 53, 2940-2955

Biochar Formation Mechanisms

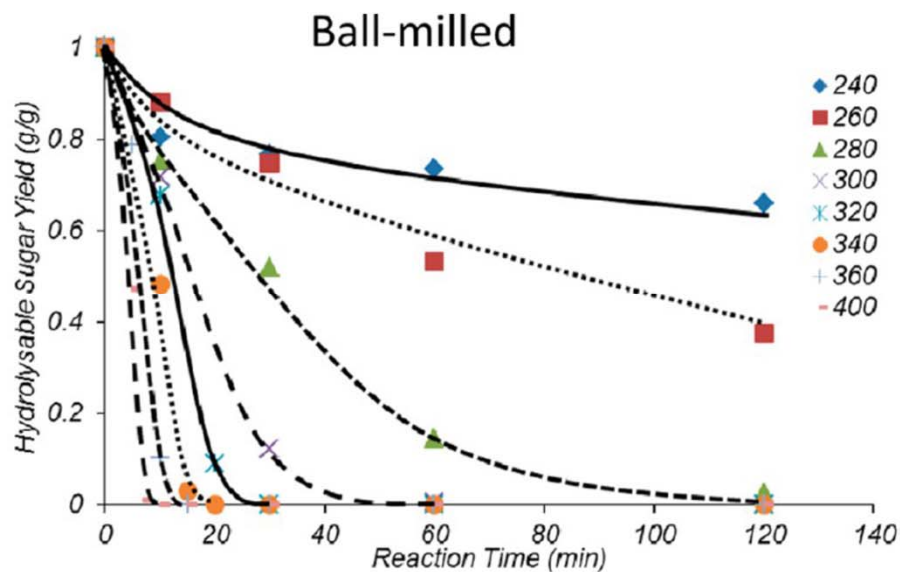
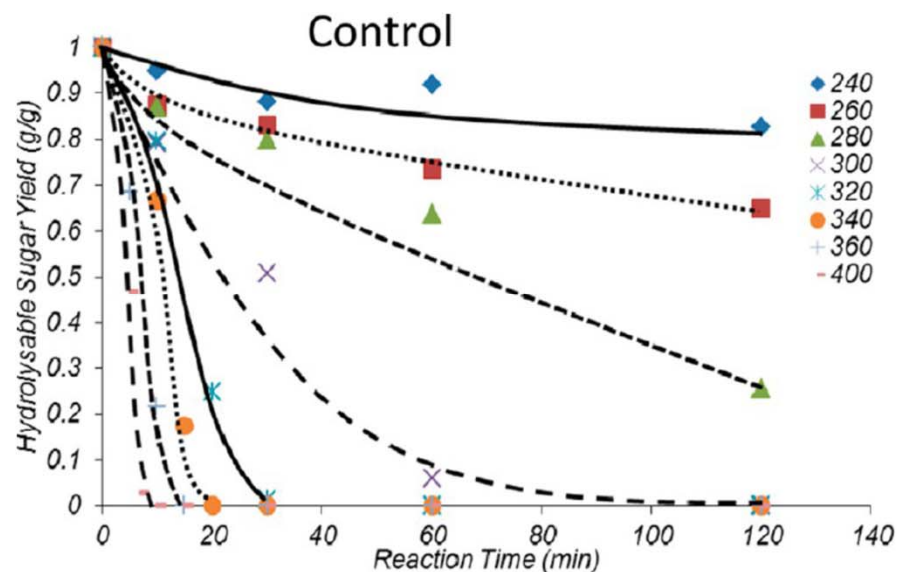
Study: Formation Mechanisms of Cellulose Char



Wang Z, Pecha B, Westerhof RJM, Kersten SRA, Li C-Z, McDonald AG, Garcia-Perez M: Effect of Cellulose Crystallinity on Solid/Liquid Phase Reactions Responsible for the Formation of Carbonaceous Residues during Pyrolysis. Industrial & Engineering Chemistry Research, 2014, 53, 2940-2955

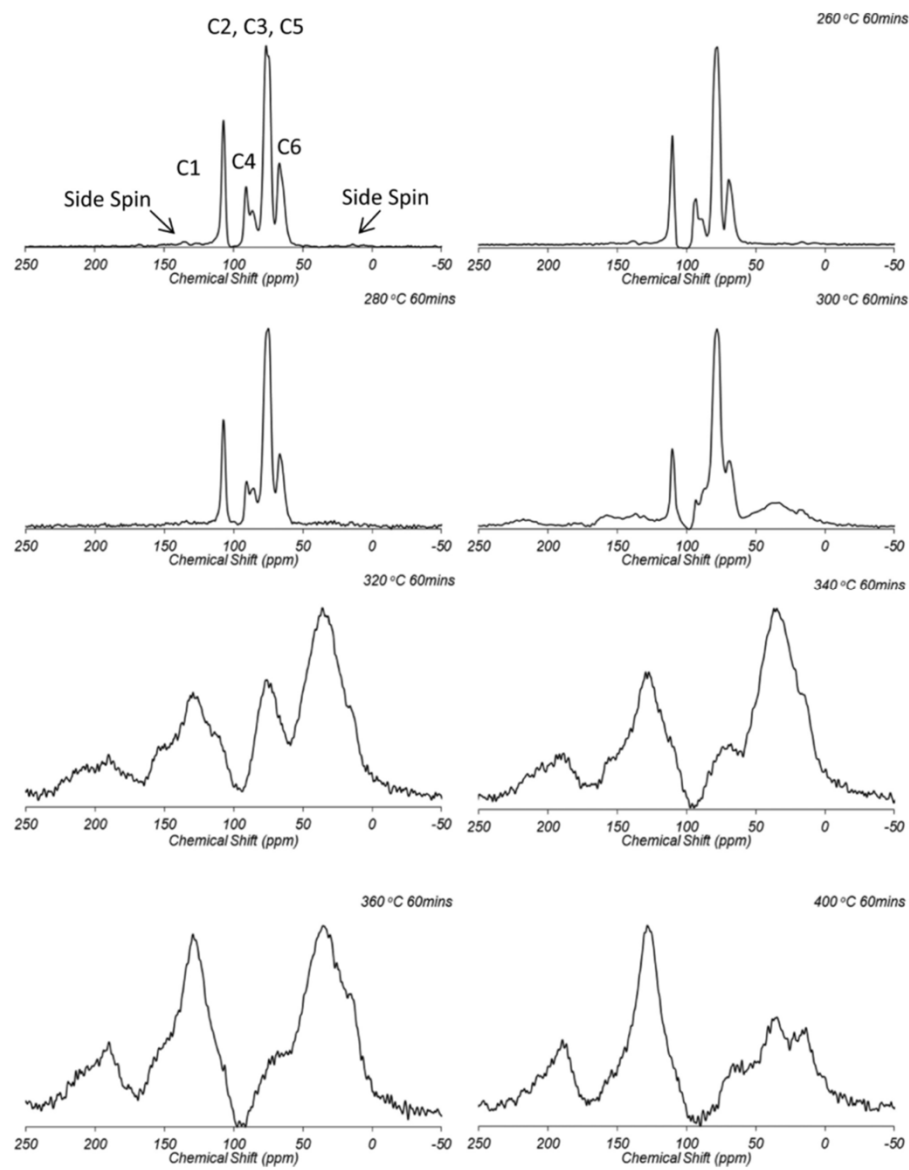
Biochar Formation Mechanisms

Content of hydrolysable sugar



Wang Z, Pecha B, Westerhof RJM, Kersten SRA, Li C-Z, McDonald AG, Garcia-Perez M: Effect of Cellulose Crystallinity on Solid/Liquid Phase Reactions Responsible for the Formation of Carbonaceous Residues during Pyrolysis. *Industrial & Engineering Chemistry Research*, 2014, 53, 2940-2955

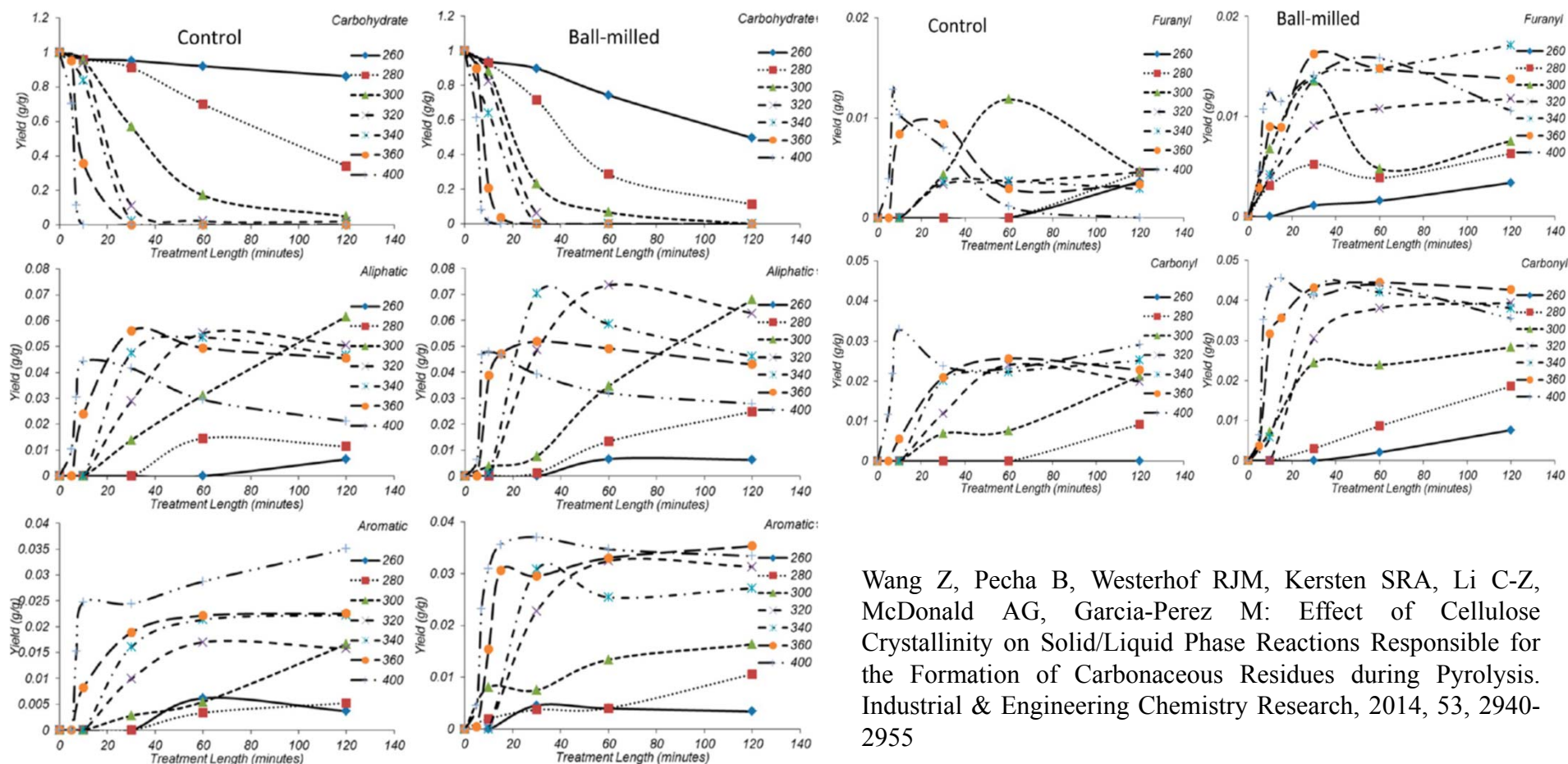
Biochar Formation Mechanisms



Wang Z, Pecha B, Westerhof RJM, Kersten SRA, Li C-Z, McDonald AG, Garcia-Perez M: Effect of Cellulose Crystallinity on Solid/Liquid Phase Reactions Responsible for the Formation of Carbonaceous Residues during Pyrolysis. Industrial & Engineering Chemistry Research, 2014, 53, 2940-2955

Biochar Formation Mechanisms

Yield of carbohydrate, aliphatic, aromatic, furanyl and carbonyl groups

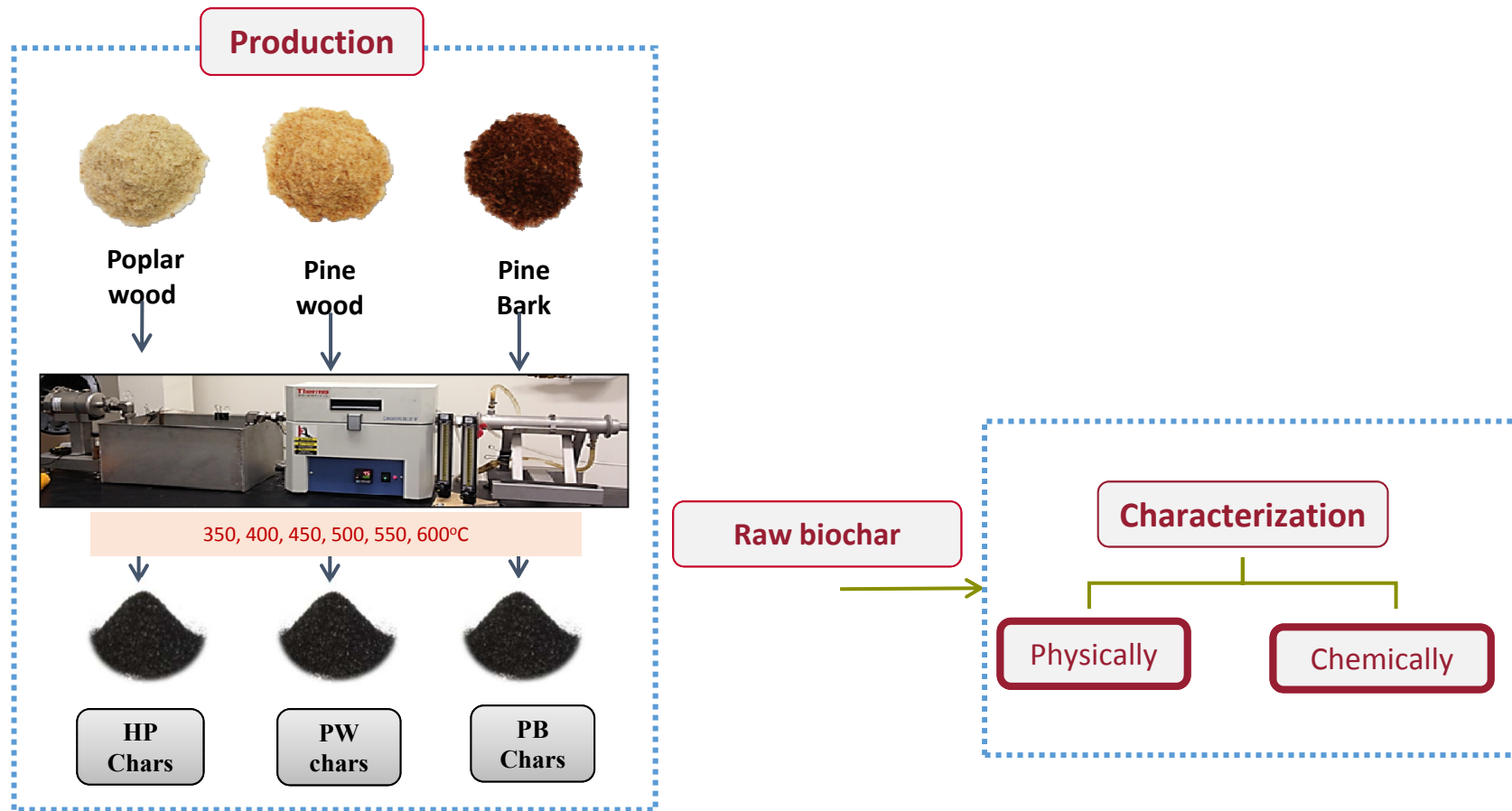


Wang Z, Pecha B, Westerhof RJM, Kersten SRA, Li C-Z, McDonald AG, Garcia-Perez M: Effect of Cellulose Crystallinity on Solid/Liquid Phase Reactions Responsible for the Formation of Carbonaceous Residues during Pyrolysis. Industrial & Engineering Chemistry Research, 2014, 53, 2940-2955

The relationship between biochar structure, composition and adsorption capacity is poorly known

Biochar Properties

Study: Effect of Pyrolysis Temperature



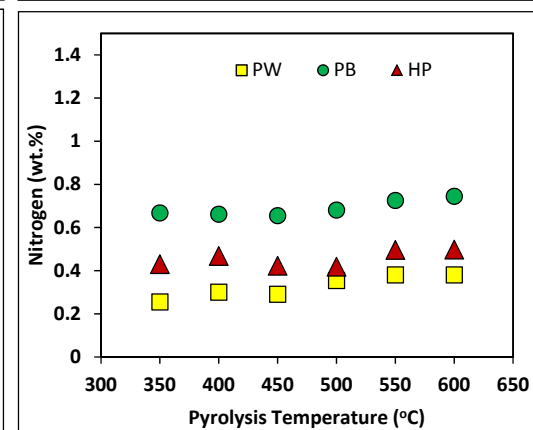
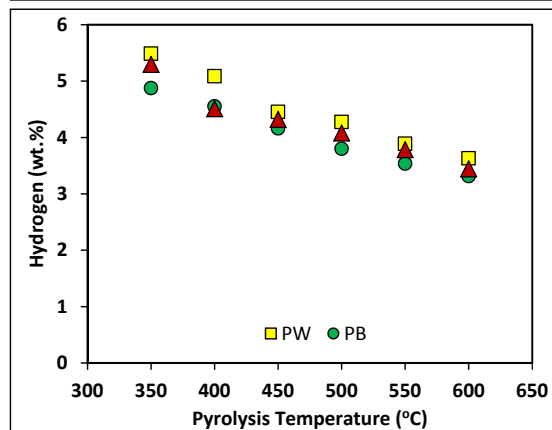
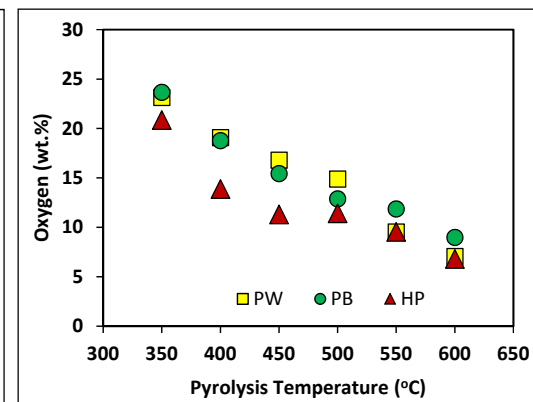
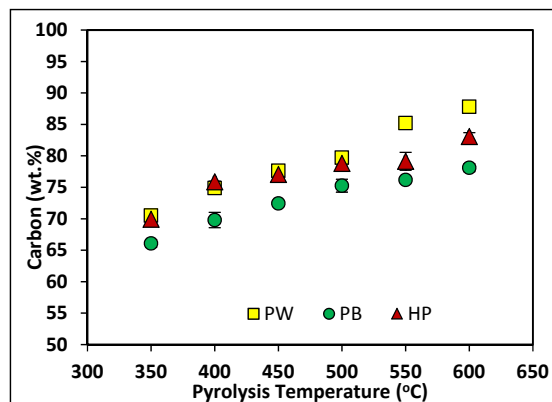
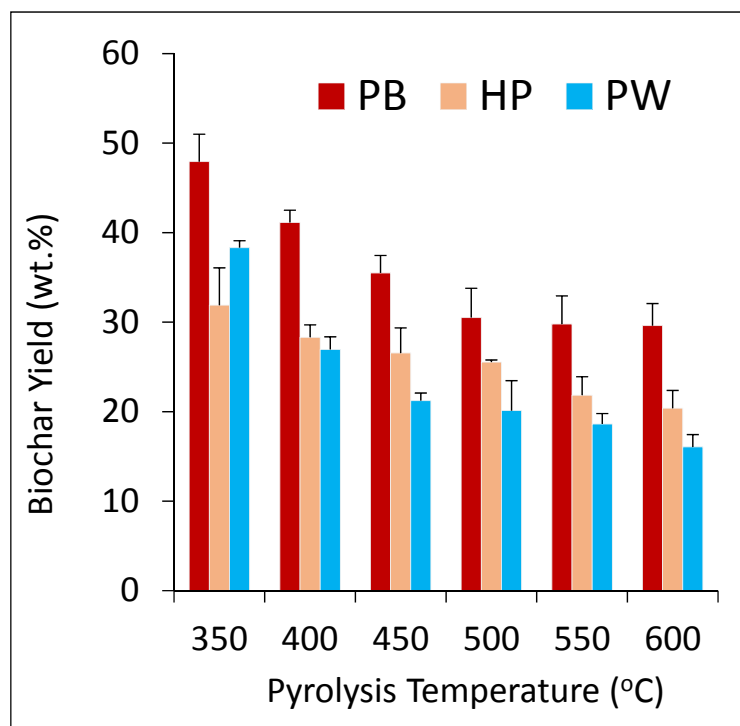
Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, **2016**, pp 37-48

Biochar Properties

Effect of Pyrolysis Temperature

Elemental Composition

Yield of Char

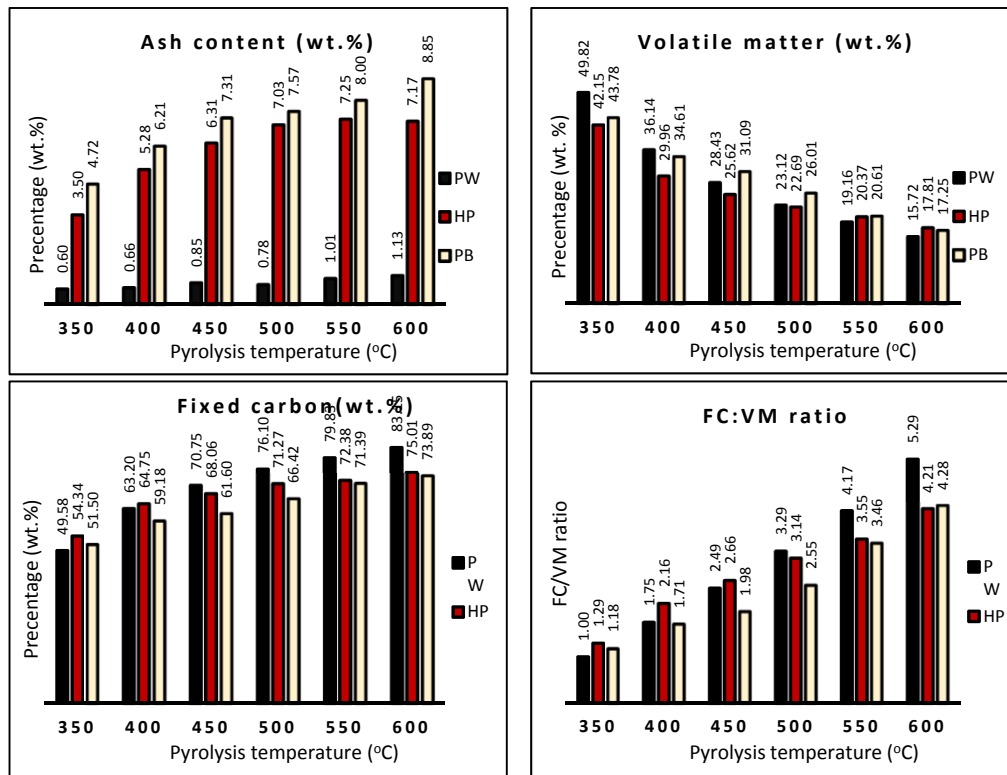


Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, 2016, pp 37-48

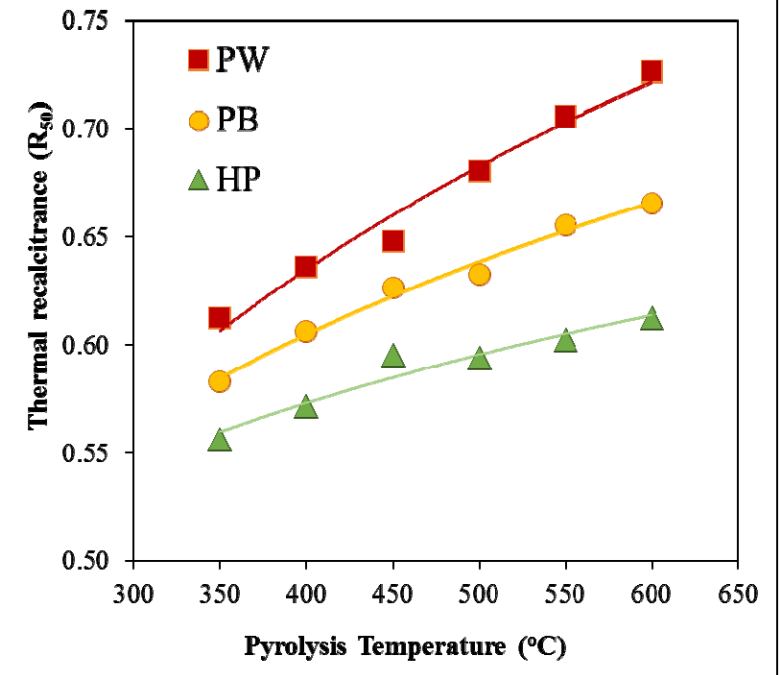
Biochar Properties

Effect of Pyrolysis Temperature

Proximate analysis



Thermal recalcitrance



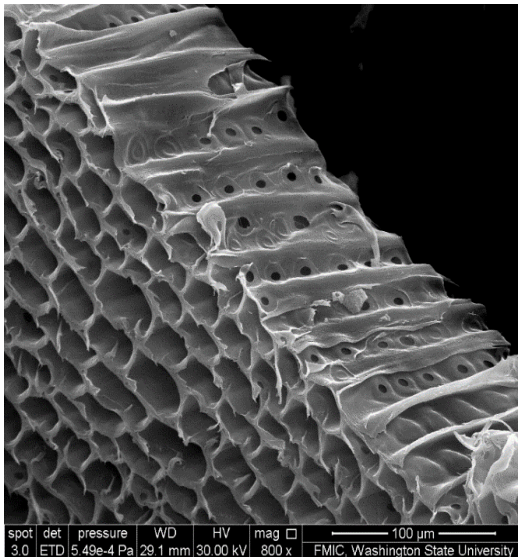
$$R_{50, \text{ biochar}} = T_{50, \text{ biochar}} / T_{50, \text{ graphite}}$$

$T_{50, \text{ biochar}}$ and $T_{50, \text{ graphite}}$ were the temperature values corresponding to 50% weight loss by oxidation/volatilization of biochar and graphite

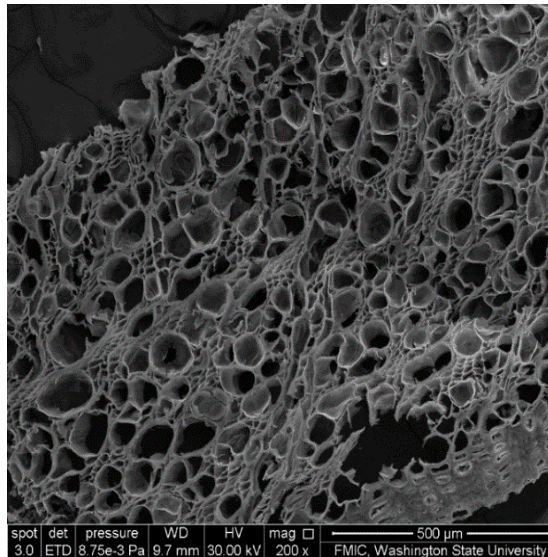
Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, 2016, pp 37-48

Biochar Properties

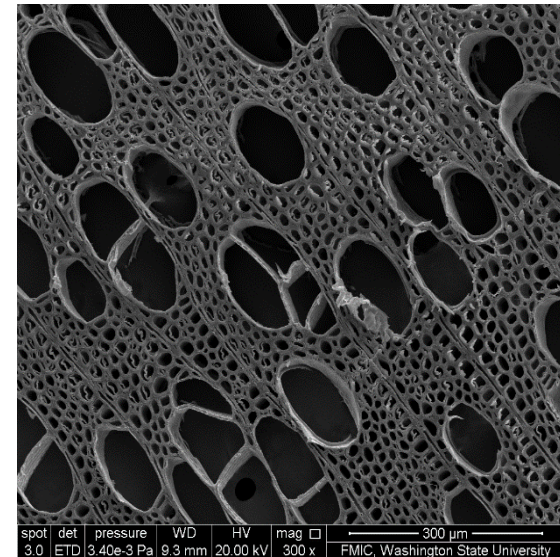
SEM Analysis



Pine wood biochar
mag. 800X



Pine bark biochar
mag. 200X

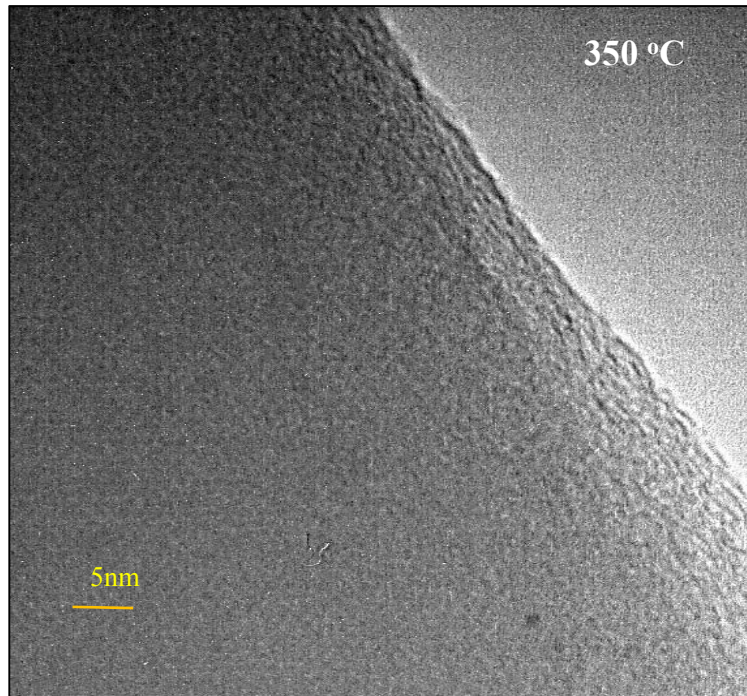


Poplar wood biochar
mag. 300X

Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, **2016**, pp 37-48

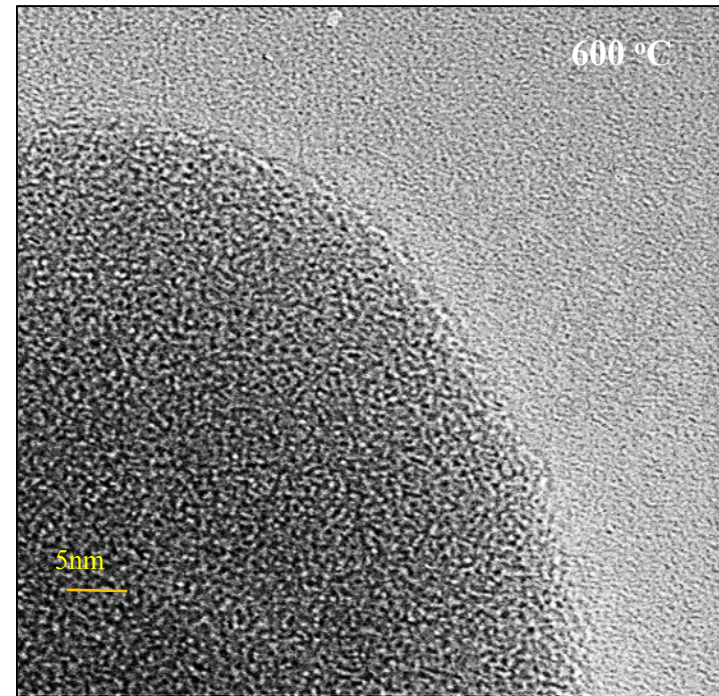
Biochar Properties

TEM Analysis



Pine wood biochar - 350°C

mag. 310 kX



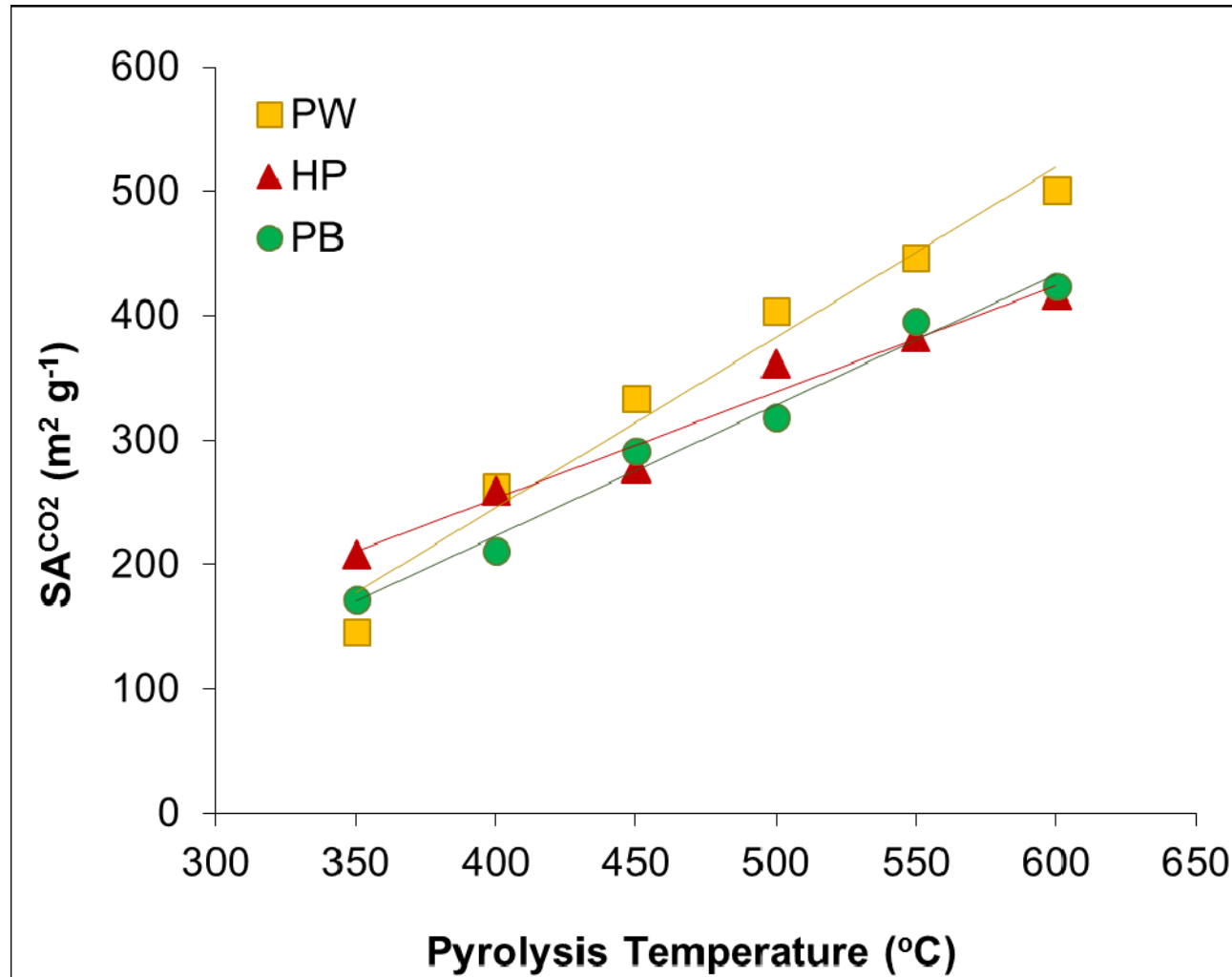
Pine wood biochar - 600°C

mag. 310 kX

Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, **2016**, pp 37-48

Biochar Properties

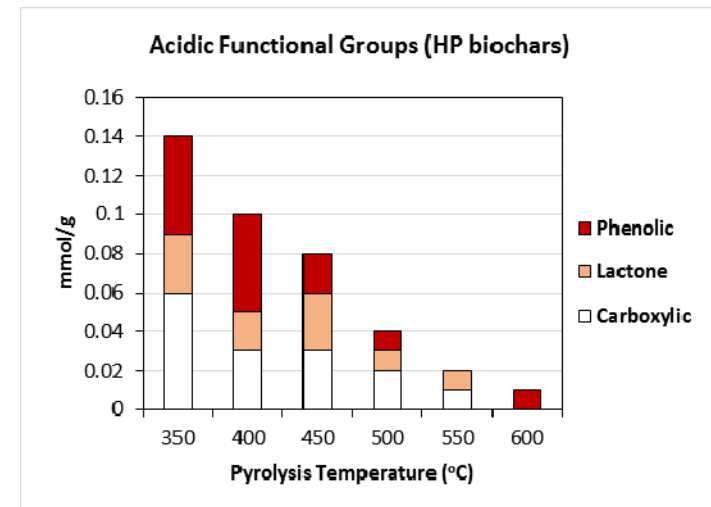
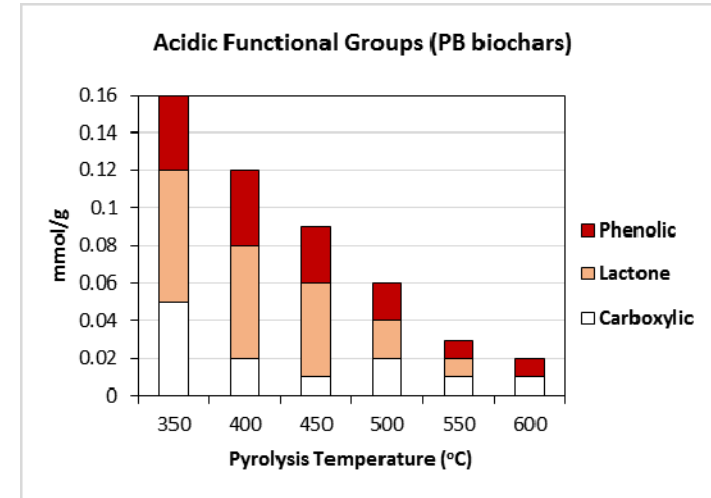
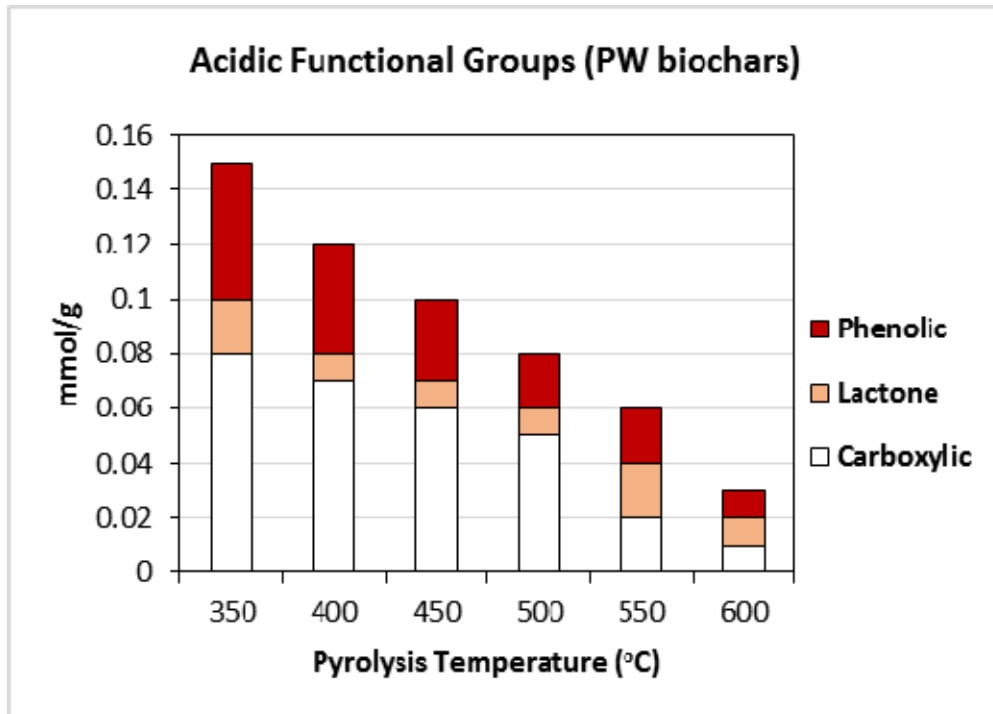
Surface Area



Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, 2016, pp 37-48

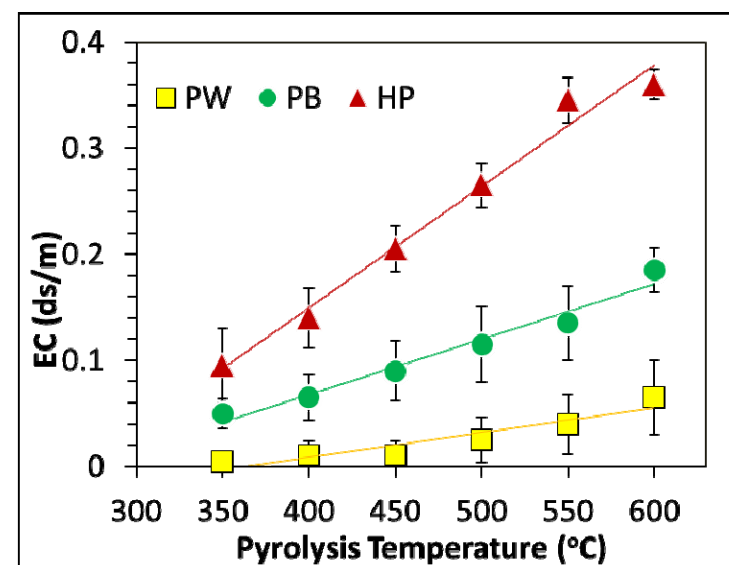
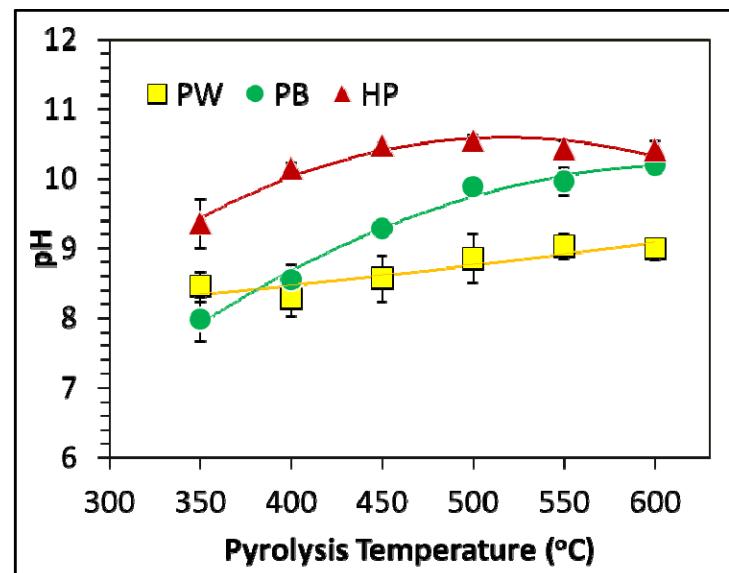
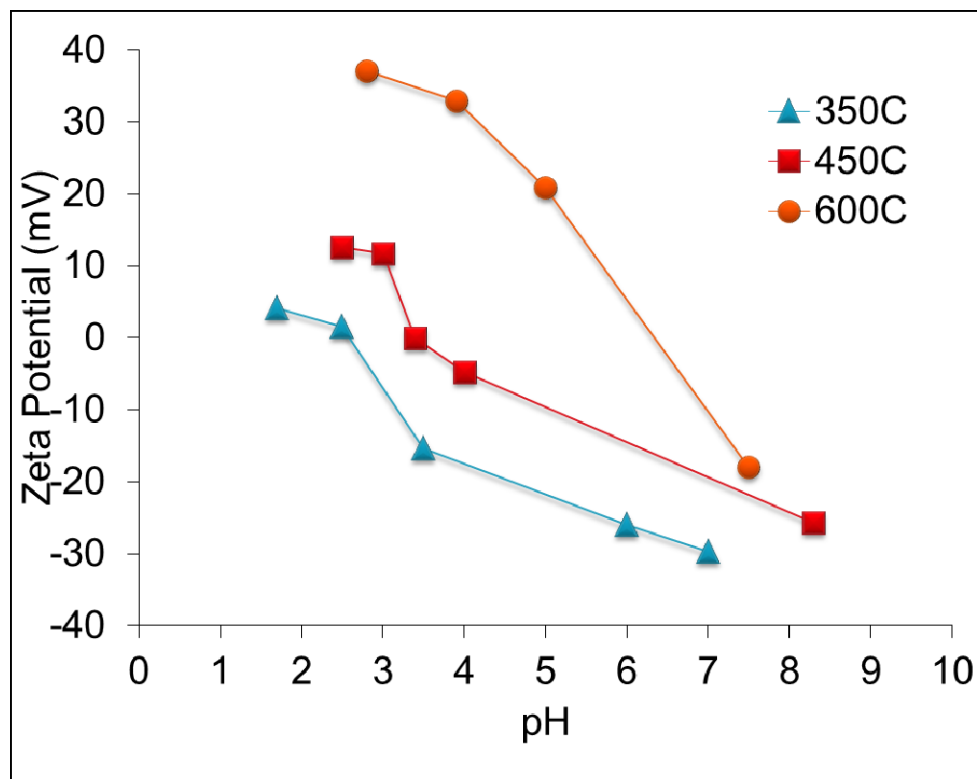
Biochar Properties

Total Acidic Functional Groups (Boehm titration)



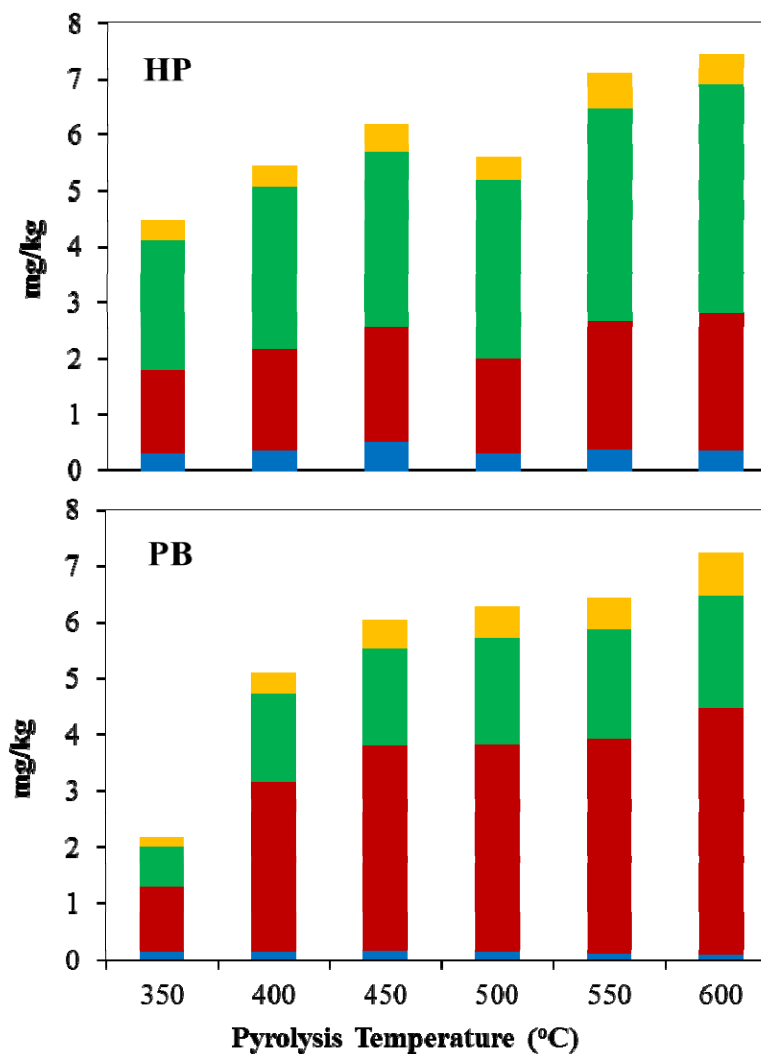
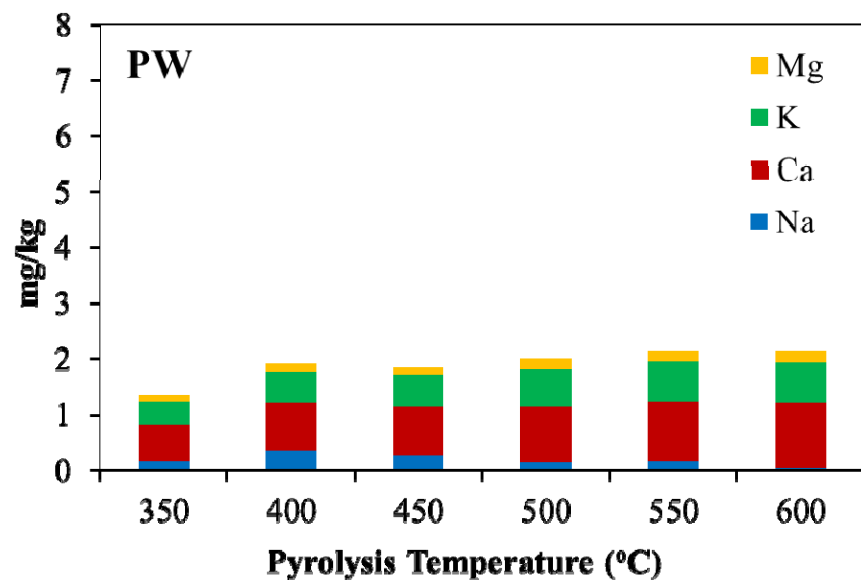
Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, 2016, pp 37-48

Biochar Properties



Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, 2016, pp 37-48

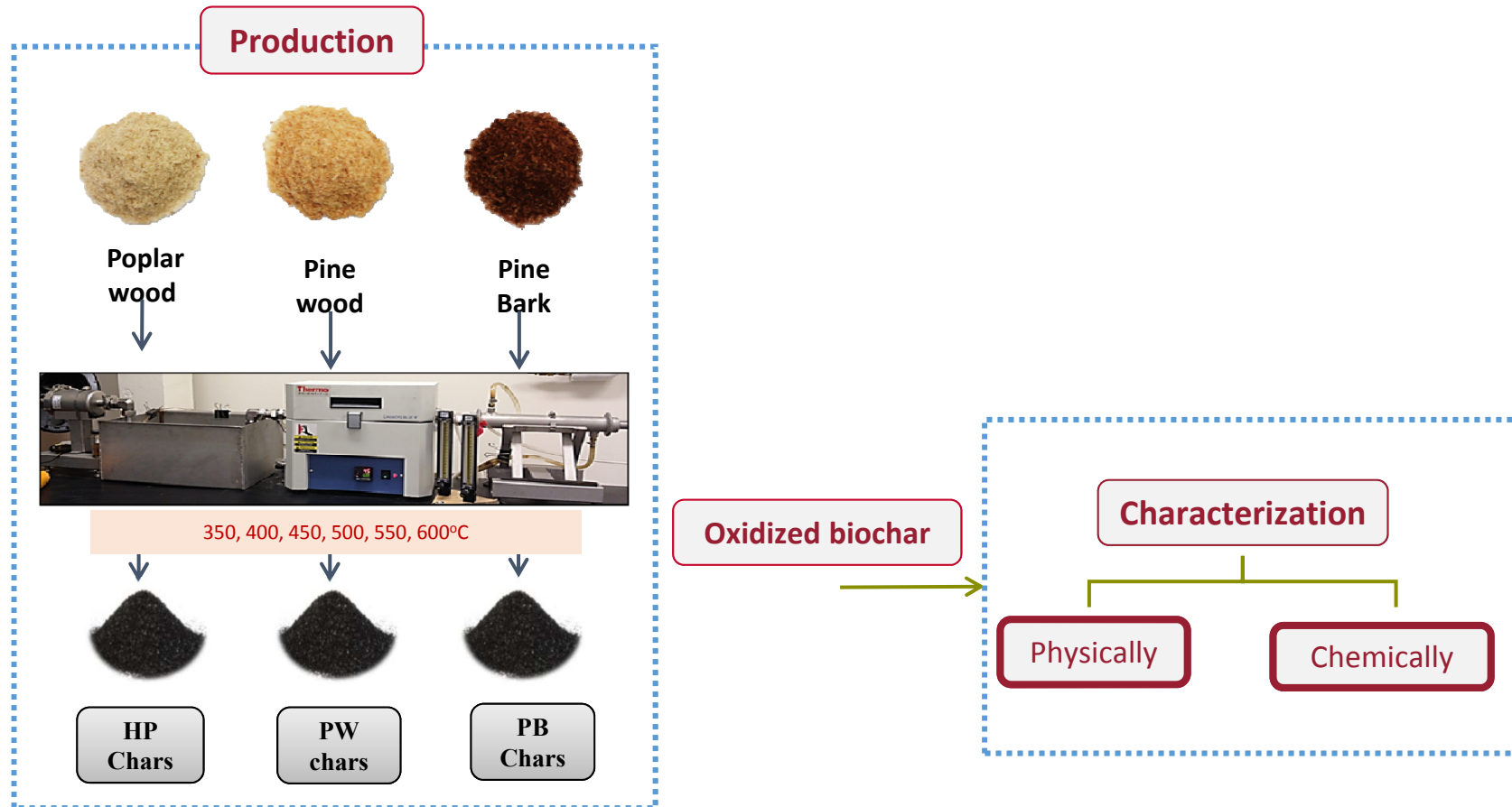
Biochar Properties



Suliman WSO, Harsh J, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Influence of Feedstock Source and Pyrolysis Temperature on Biochar Bulk and Surface Properties. *Biomass and Bioenergy*, Volume 84, 2016, pp 37-48

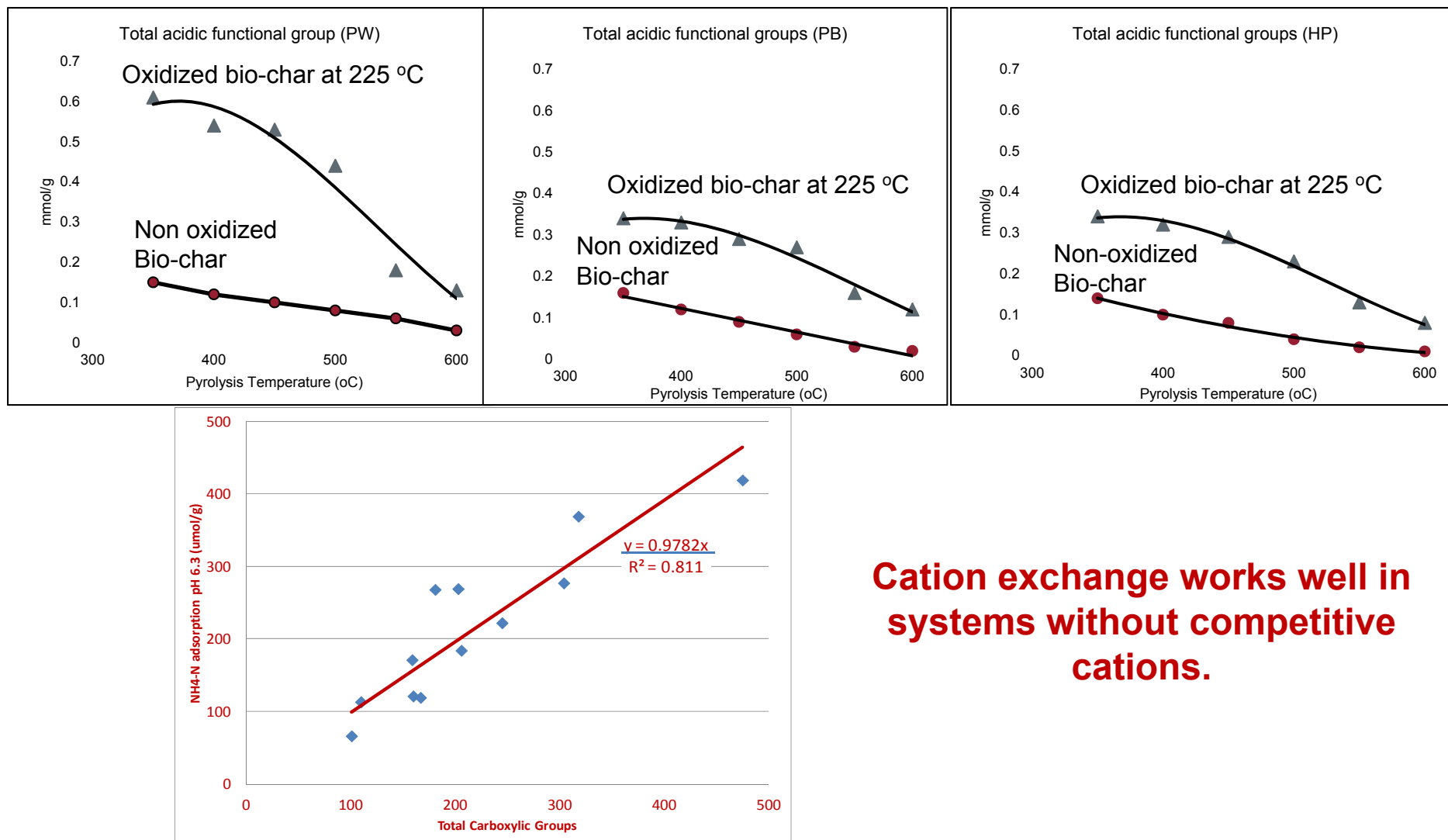
Biochar Properties

Study: Effect of Air Oxidation



Suliman W, Harsh JB, Abu-Lail NI, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Modification of Biochar Surface by Air Oxidation: Role of Pyrolysis Temperature. *Biomass and Bioenergy*, Vol.85, February **2016**, pp 1-11.

Biochar Properties



Cation exchange works well in systems without competitive cations.

Smith M, Ha S, Amonette JE, Dallmeyer I, Garcia-Perez M: Enhancing cation exchange capacity of chars through ozonation. Biomass and Bioenergy, 81, 2015, 304-314

Suliman W, Harsh JB, Abu-Lail N, Fortuna A-M, Dallmeyer I, Garcia-Perez M: Modification of biochar surface by air oxidation: Role of pyrolysis temperature. Biomass and Bioenergy, 85, 2016, 1-11

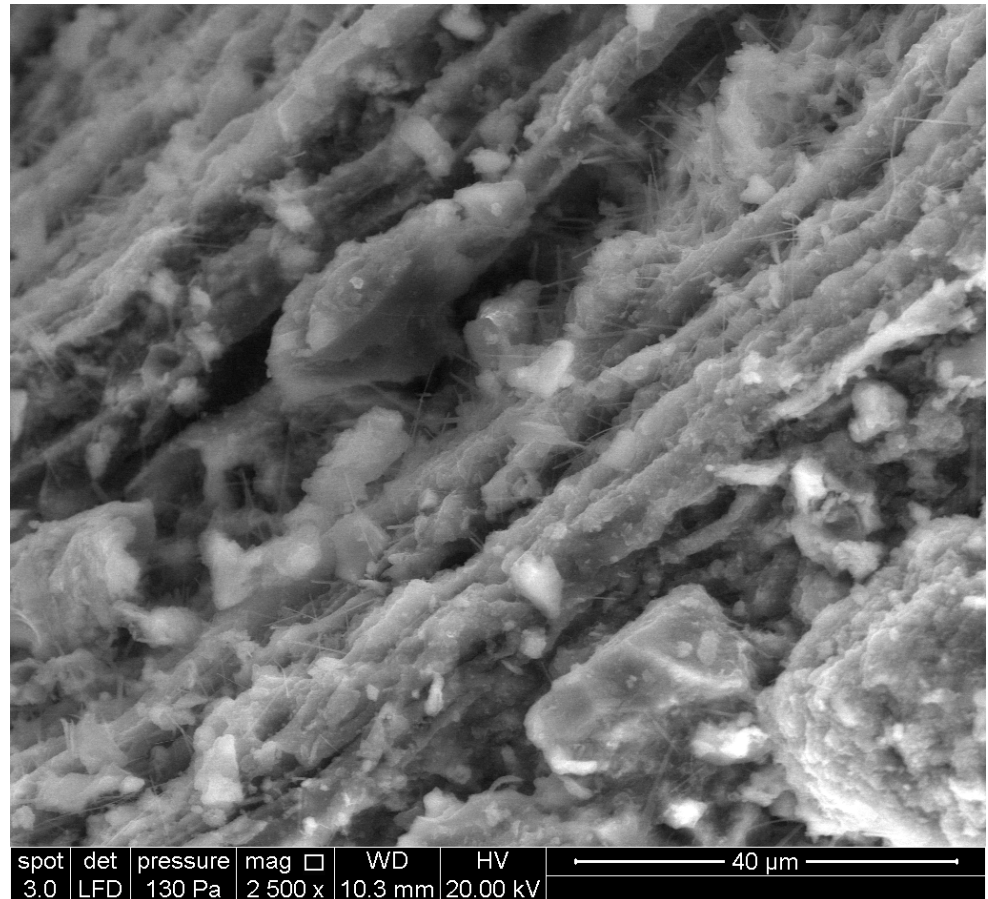
Environmental Services

Phosphate Precipitation

Precipitation of calcium for phosphate retention

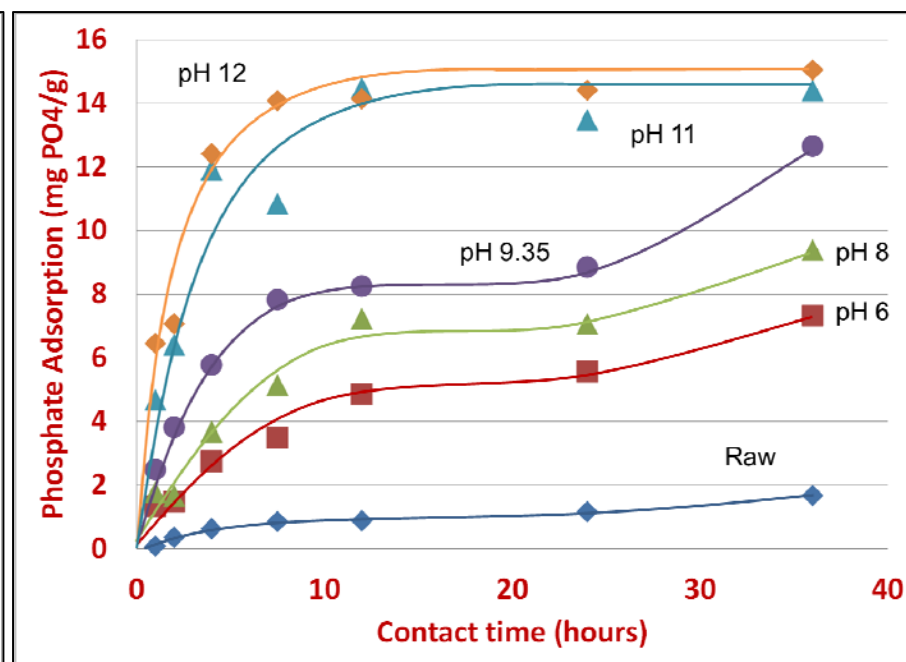
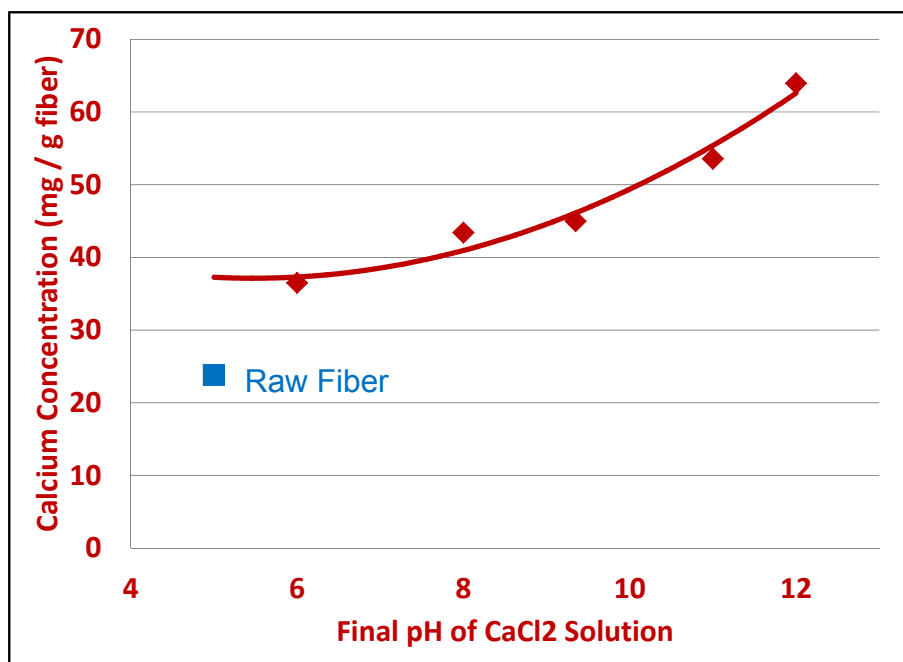
AD fiber was acid washed in 2% nitric acid and impregnated with calcium by immersion in a CaCl_2 solution followed by pH adjustment to 6, 8, 9.35, 11 and 12

Modified fiber samples were then dried and pyrolyzed at 500°C for 30 minutes using a spoon reactor



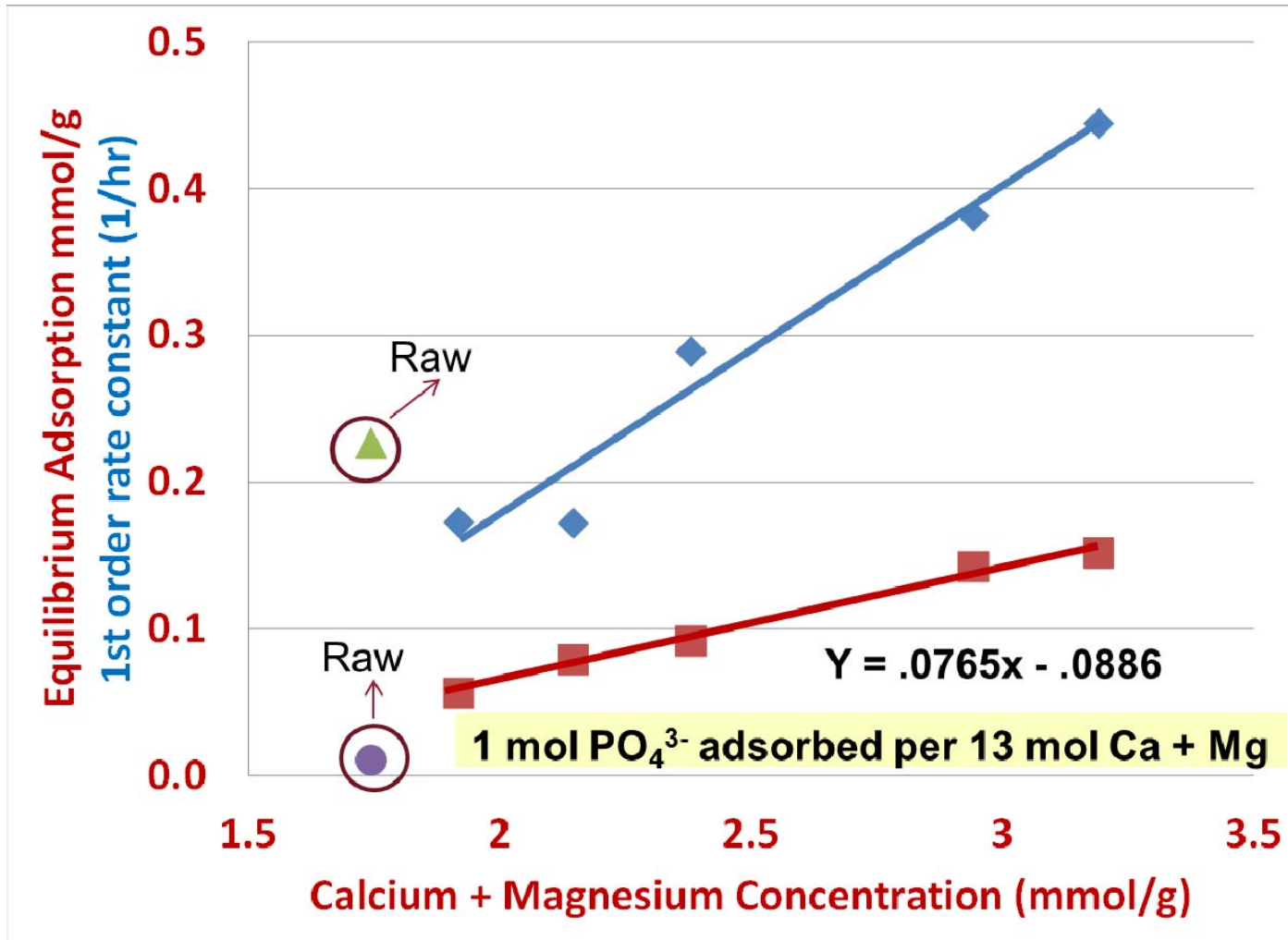
Environmental Services

Pre-pyrolysis CaCl_2 modification of AD fiber



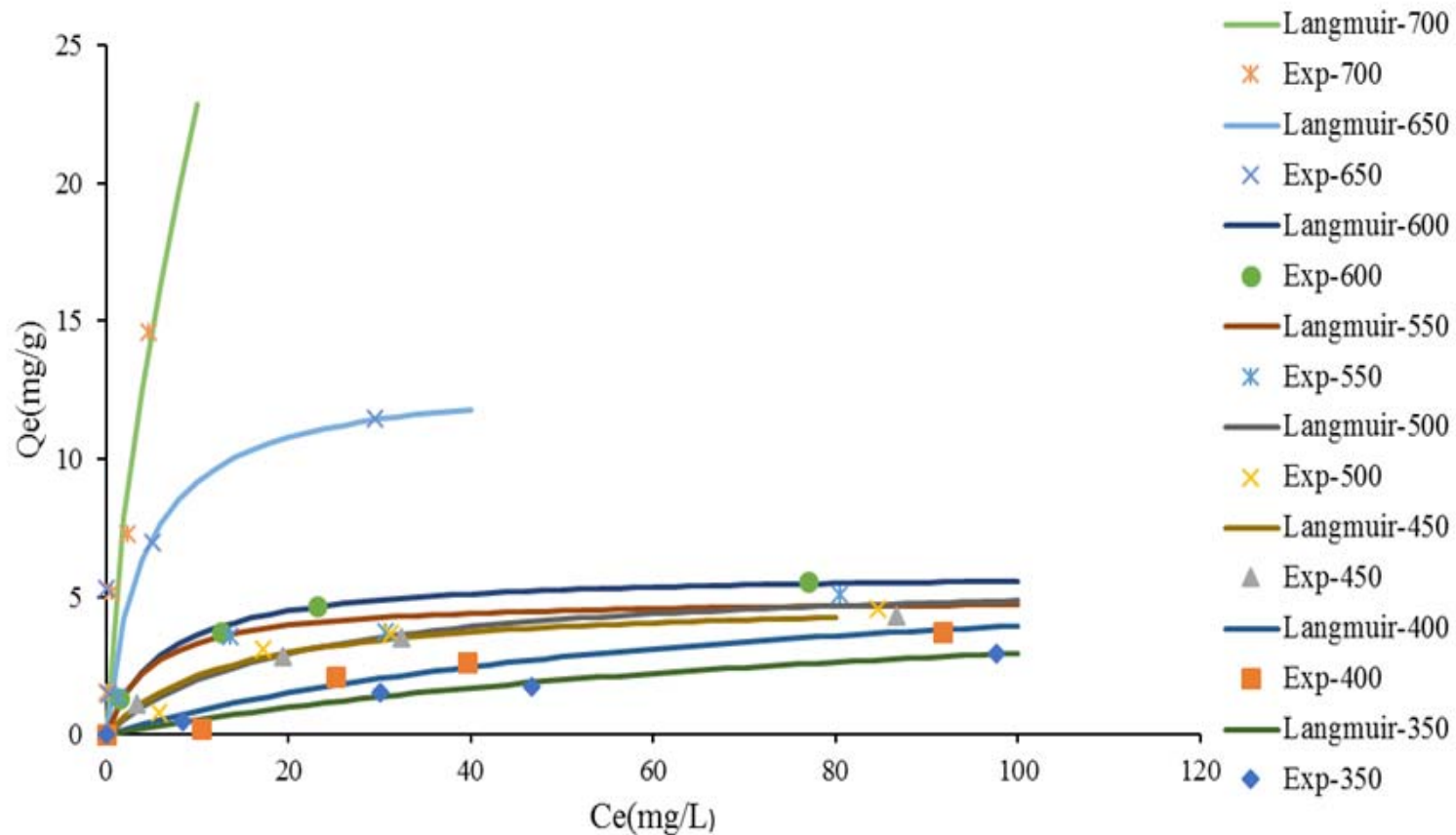
Environmental Services

Phosphorous Removal



Environmental Services

Study: Adsorption isotherms of PO_4^{3-} on activated carbon produced from Anaerobic Digested Fiber at different temperatures



Environmental Services

Bio-chars for Phosphate Removal



**Digested Dairy Manure
Fiber**



Pelletized Manure



Pyrolysis



**Digested Fiber Bio-
char**

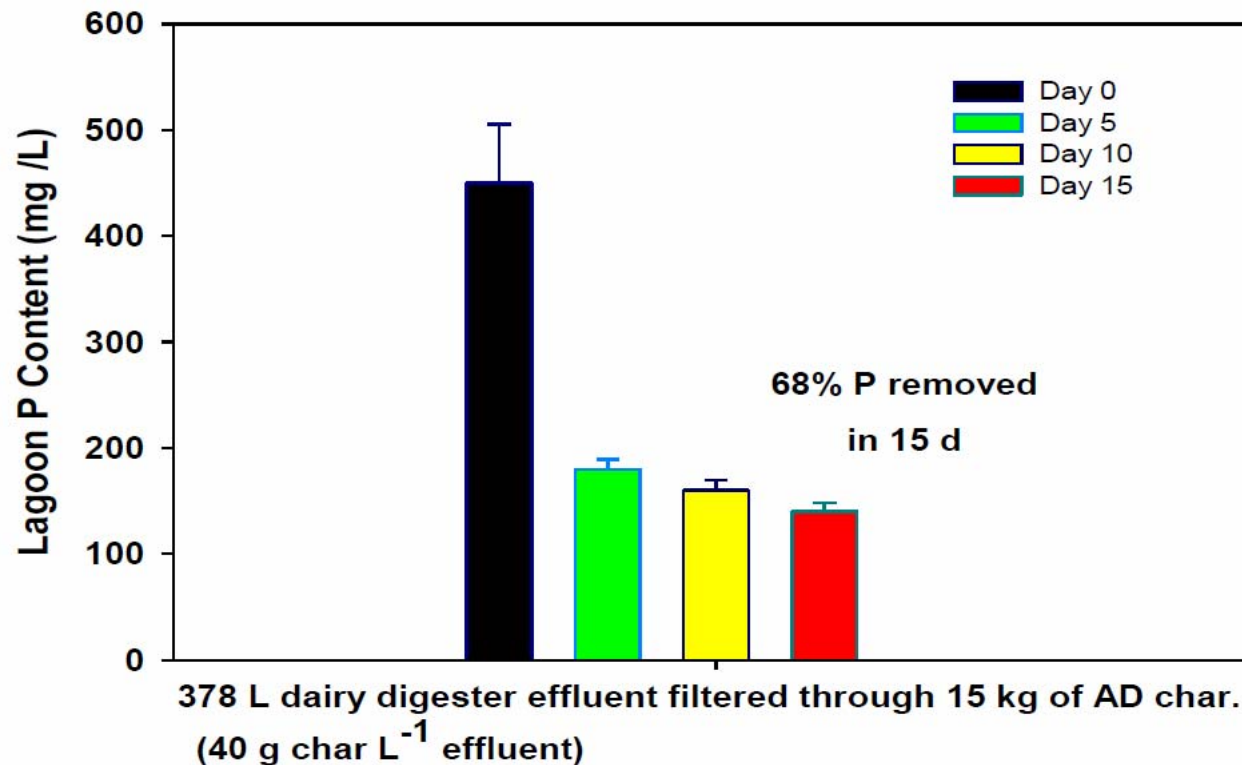


Streubel J, Kruger CE, Granatstein D, Collins H.P.: Bio-char Sorption of Phosphorus from Dairy Manure Lagoons. Future of Energy Conference. Seattle, WA, 2010

Streubel J, Biochar: Its characterization and utility for recovering phosphorous from Anaerobic Digested Dairy Effluent. PhD dissertation WSU, May 2011.

Environmental Services

Bio-chars for Phosphate Removal

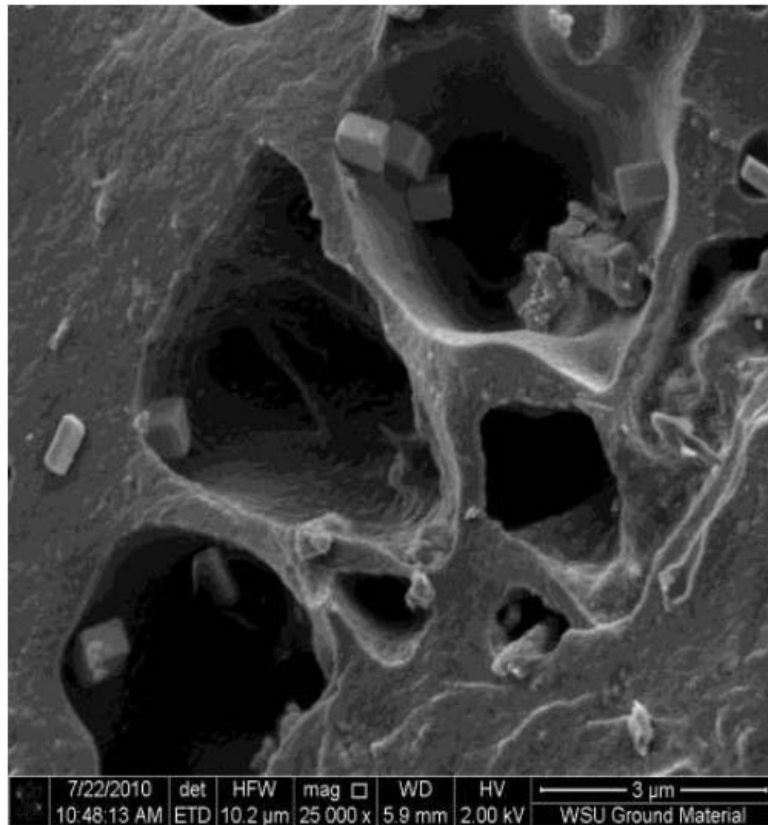


Anaerobic digested bio-char can be effectively used to reduce phosphorous from dairy lagoons.

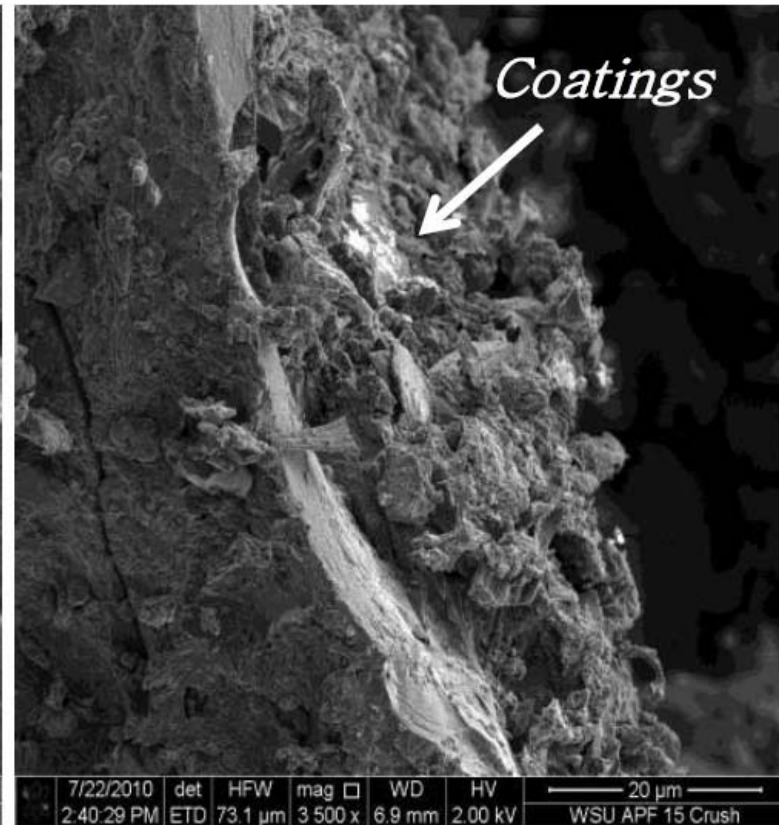
Streubel J, Kruger CE, Granatstein D, Collins H.P.: Bio-char Sorption of Phosphorus from Dairy Manure Lagoons. Future of Energy Conference. Seattle, WA, 2010

Streubel J, Biochar: Its characterization and utility for recovering phosphorous from Anaerobic Digested Dairy Effluent. PhD dissertation WSU, May 2011.

Environmental Services



Un-Amended Char



Lagoon-treated

Most of the phosphorous removed seems to be in the colloidal form

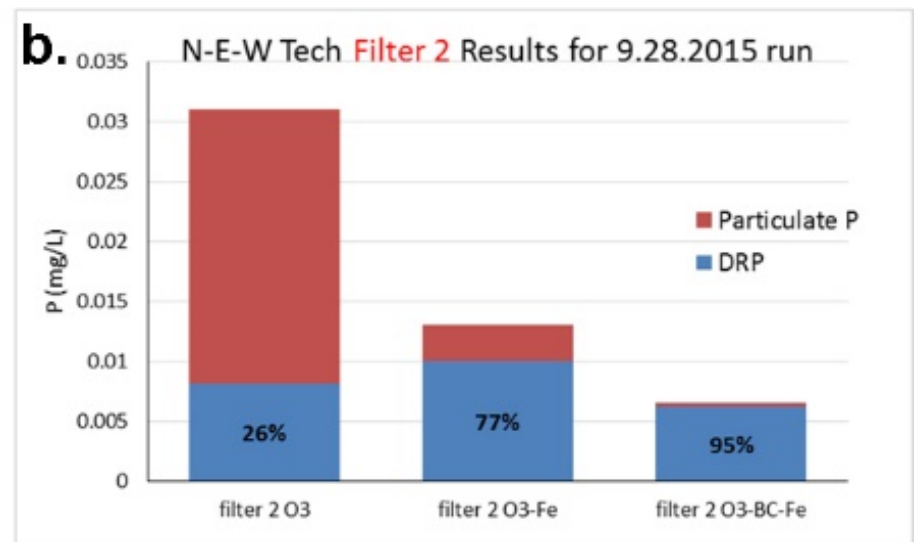
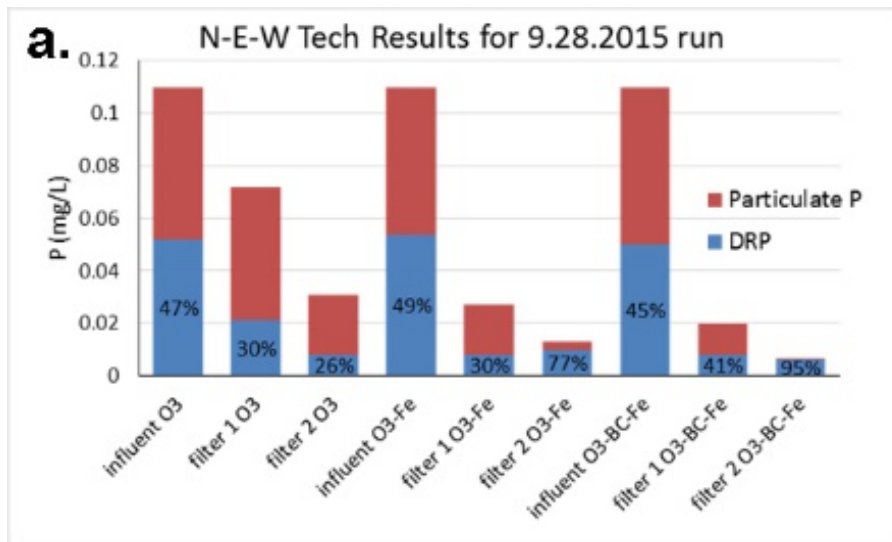
Streubel J, Kruger CE, Granatstein D, Collins H.P.: Bio-char Sorption of Phosphorus from Dairy Manure Lagoons. Future of Energy Conference. Seattle, WA, 2010

Streubel J, Biochar: Its characterization and utility for recovering phosphorous from Anaerobic Digested Dairy Effluent. PhD dissertation WSU, May 2011.

Engineered Biochars

Phosphorous Removal

Prof. Greg Moller UI

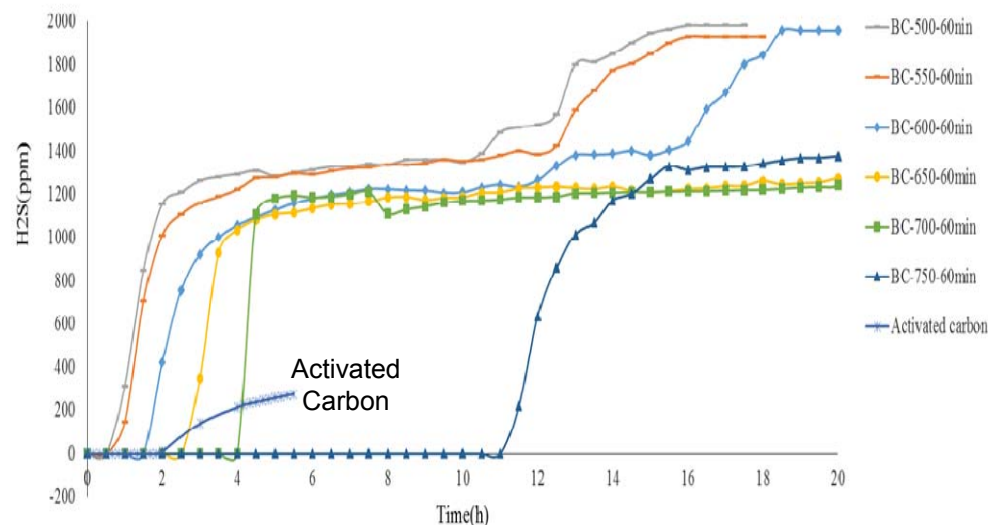
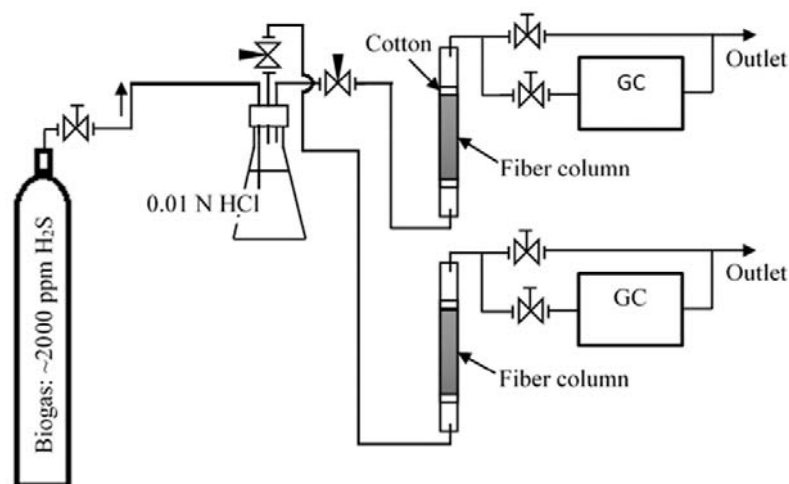


DRP: Dissolved Reactive Phosphorous

Greg Moller: N-E-W Tech™: Design-build of an intensification resource recovery (IR2) technology at the Nutrient, Energy, Water nexus. University of Idaho

Environmental Services

Study: H₂S removal from biogas with Anaerobic digested fiber



Bio-char derived from anaerobic digested fiber can be an excellent adsorbent for H₂S removal from biogas.

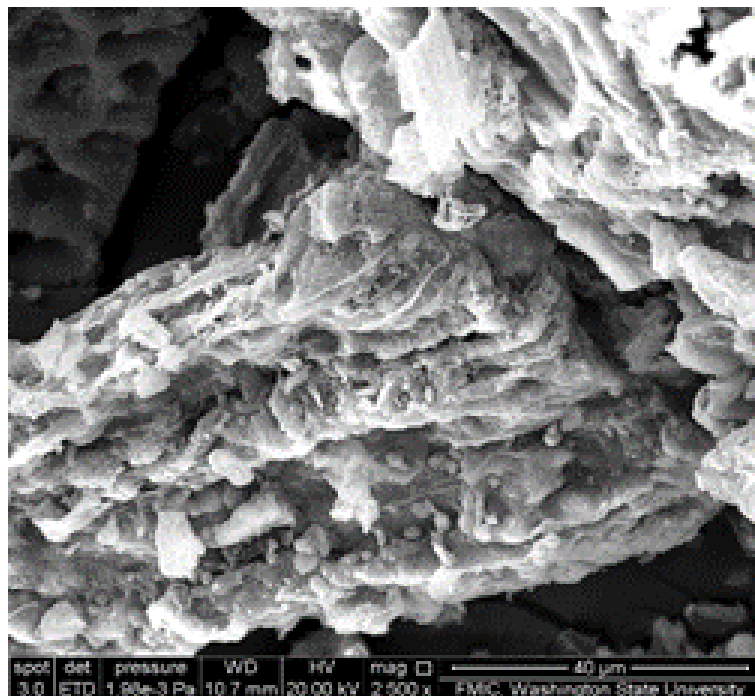
The resulting biochar contains 10-28 % of Sulfur on the surface

Pelaez-Samaniego MR, Smith MW, Zhao QZ, Garcia-Perez T, Frear C, Garcia-Perez M: Charcoal from Anaerobically digested dairy fiber for removal of hydrogen sulfide within biogas. In preparation, 2017

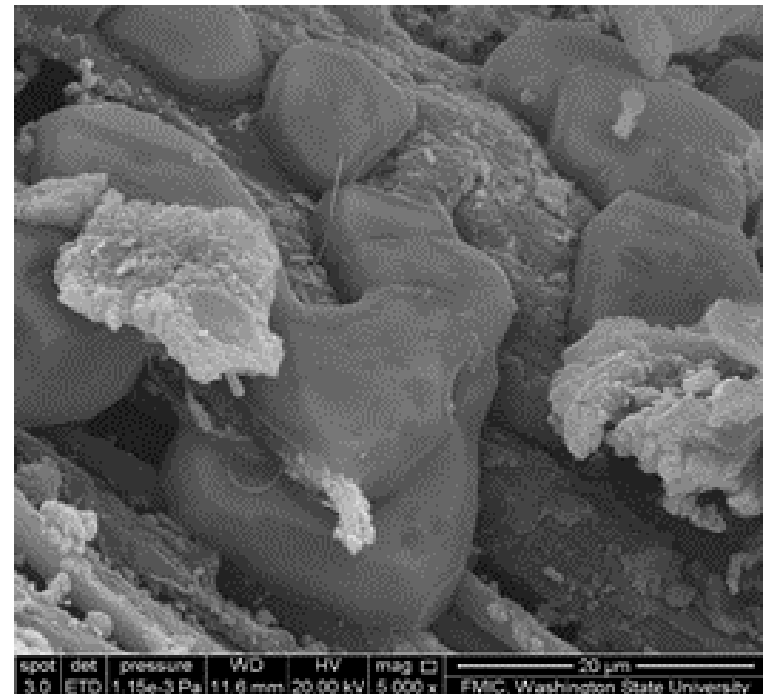
Environmental Services

Study: H₂S removal from biogas with Anaerobic digested fiber

Char



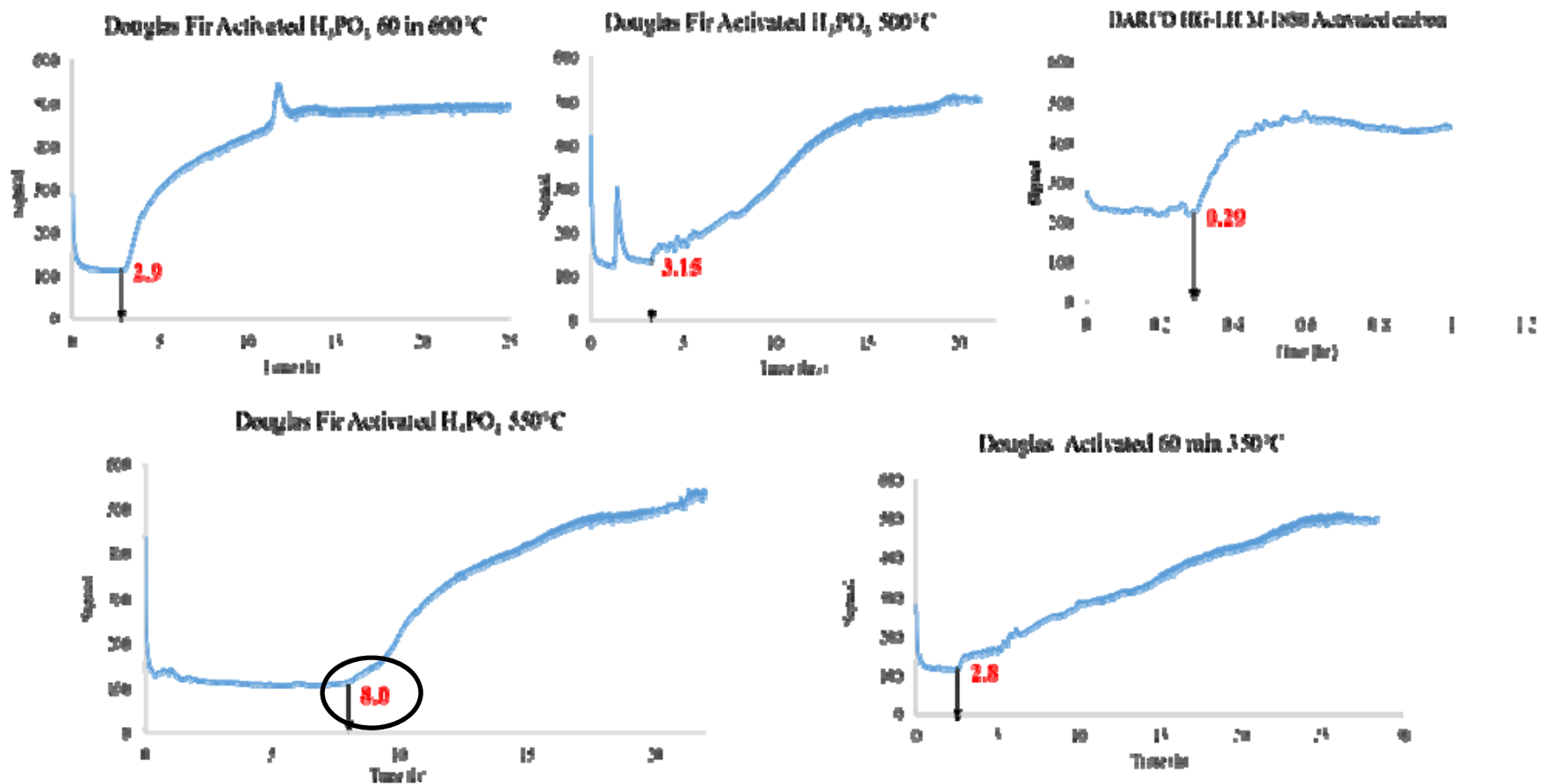
S on char surface after H₂S adsorption



Pelaez-Samaniego MR, Smith MW, Zhao QZ, Garcia-Perez T, Frear C, Garcia-Perez M: Charcoal from Anaerobically digested dairy fiber for removal of hydrogen sulfide within biogas. In preparation, 2017

Environmental Services

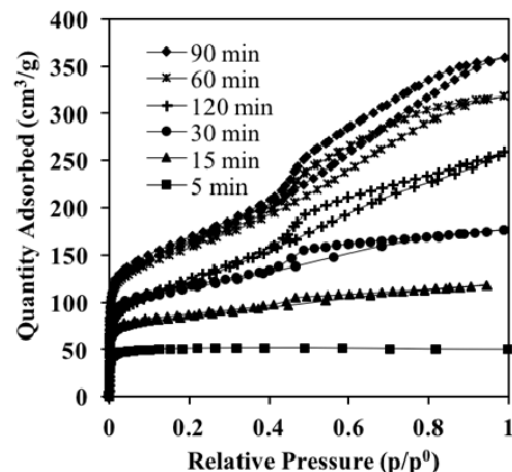
Study: Ammonia adsorption breakthrough curves of biochar produced at different temperature (DF Chemically Activated Carbon (with H_3PO_4))



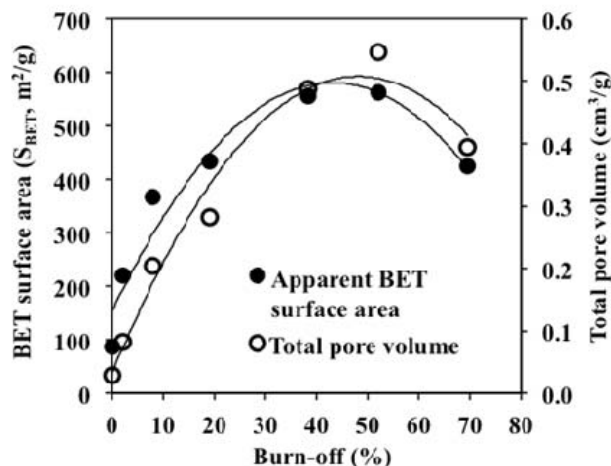
Environmental Services

Physical activation of a novel type of lignin (sulfite-pretreated, saccharified Douglas Fir forest harvest residues (FRS) (CO₂ activation at 700 °C).

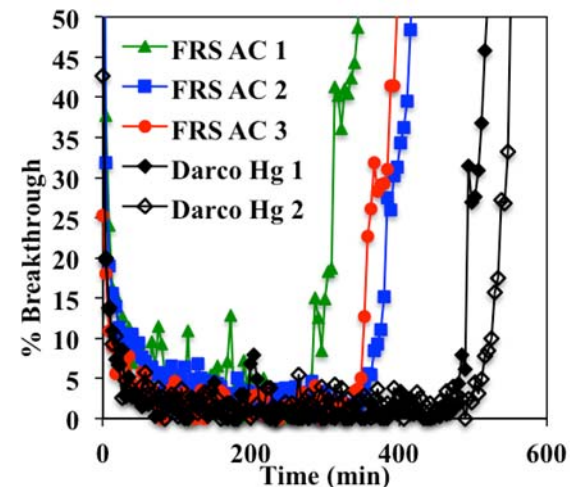
N₂ adsorption-desorption isotherms



Optimal Activation Conditions



Breakthrough curves of mercury



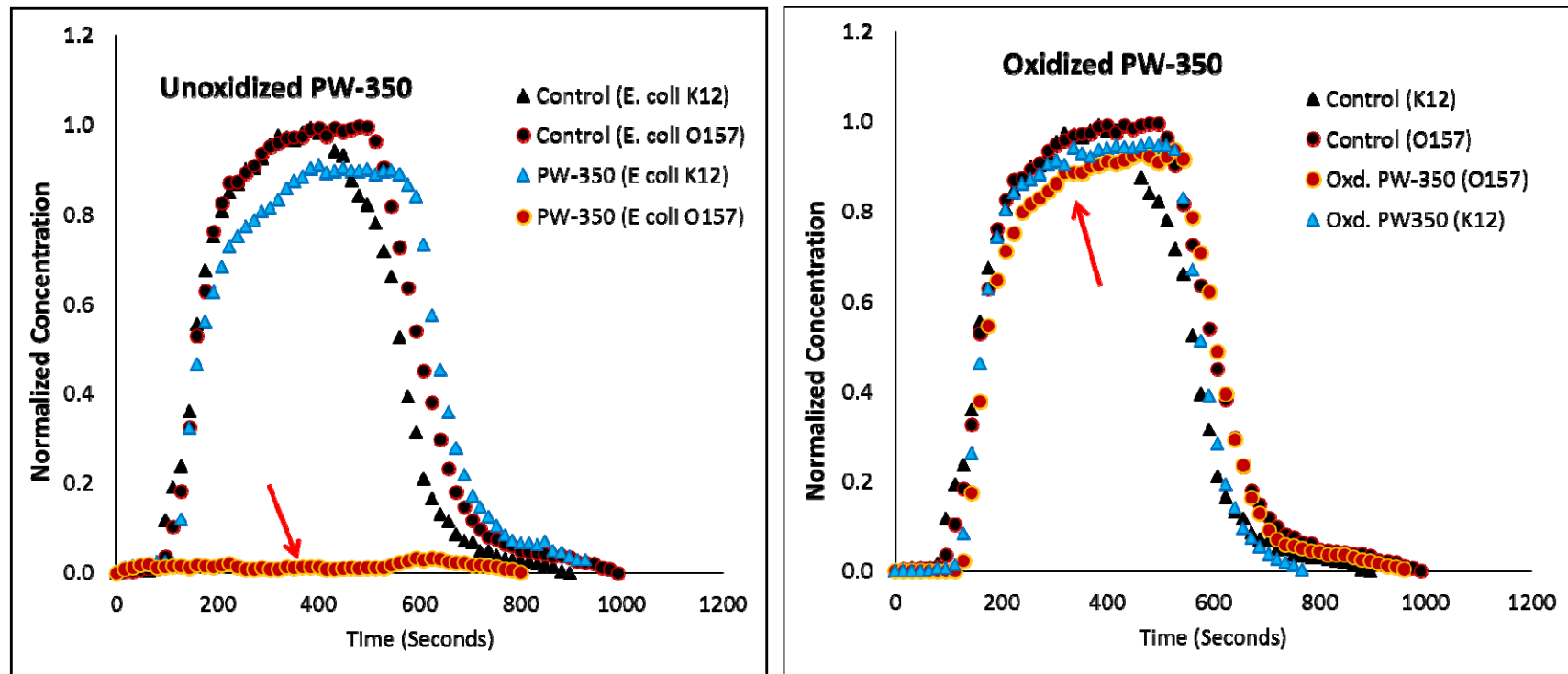
Summary of adsorption results

Carbon	S _{BET} (m ² /g)	V _{total} (cm ³ /g)	V _{meso} (cm ³ /g)	V _{micro} (cm ³ /g)	Inlet [Hg ⁰] in flue gas (μg Hg ⁰ /Nm ³)	Equilibrium Hg ⁰ Adsorption Capacity (μg Hg ⁰ /g AC) @ 50 μg Hg ⁰ /Nm ³	Average Percent Hg ⁰ Removed (%)
Darco Hg	660	0.718	0.474	0.209	21.8	1133	98.5
Darco Hg	660	0.718	0.474	0.209	26.5	1226	97.8
FRS AC 1	659	0.621	0.402	0.188	27.0	674	95.1
FRS AC 2	686	0.670	0.442	0.191	25.9	863	96.0
FRS AC 3	682	0.665	0.440	0.189	21.8	857	97.6
Average (FRS AC)	676	0.652	0.428	0.189	24.9	798	96.2

FRS AC: Chars activated at 700 °C, under CO₂ for 90 min.

Environmental Services

Effects of air oxidation on e-coli removal



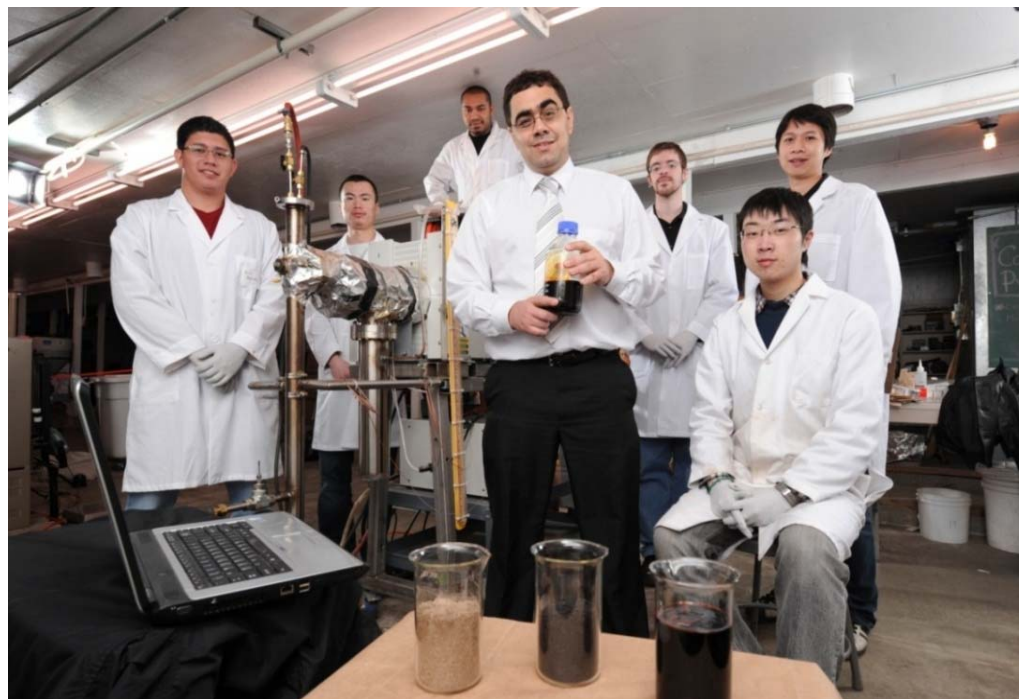
Suliman W, Harsh J, Fortuna A, Garcia-Perez M, Abu-Lail N: Towards the quantification of the effects of biochar oxidation and pyrolysis temperature on the transport of pathogenic and nonpathogenic E. coli in biochar amended sand columns (Submitted to *Environmental Science and Technology Journal*, 2016)

Conclusions

- We have proposed a new model of AD biorefinery that make use of engineered biochars for nutrients removal.
- The role of liquid intermediate as a very reactive phase responsible for many of the important reactions encountered during biomass carbonization was discussed.
- Bio-char properties depend on the feedstock used, pyrolysis conditions and post-pyrolysis treatment.
- Bio-chars capable of adsorbing phosphate, ammonia, H_2S , e-coli and mercury were developed from relevant lignocellulosic waste streams.



ACKNOWLEDGEMENT



We would like to thank the funding agencies supporting my Research Program

WASHINGTON STATE UNIVERSITY AGRICULTURAL RESEARCH CENTER

U.S. NATIONAL SCIENCE FOUNDATION

WASHINGTON STATE DEPARTMENT OF AGRICULTURE

SUN GRANT INITIATIVE, U.S. DEPARTMENT OF TRANSPORTATION, USDA

WASHINGTON STATE DEPARTMENT OF ECOLOGY

U.S. DEPARTMENT OF ENERGY

Thank you 😊

Questions?

